Nanoscale Displacement Sensing Using Surface Plasmonics Excited by Broadband Light

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Abstract

This paper presents a new displacement sensor based on surface plasmonics resonance (SPR). The displacement is obtained by measuring the change of the SPR wavelength with a fixed incident angle. Comparing to the displacement sensors based on SPR that is excited by the chromatic light source, the sensing speed of the proposed displacement sensor is improved significantly.

1 Introduction

The nanoscale displacement sensor is useful in many applications. For example, it is the heart of scanning near-field optical microscopy (SNOM) which requires the probe to be placed within 10 nm proximity of the sample surface. A SNOM basically has two operation modes. One is the constant gap mode, where the probe-sample separation has to remain constant by using atomic force feedback. The drawback of the constant gap mode is that the received optical signal is convoluted with the surface topography of the sample and this produces topographical artifacts in the SNOM image. Hence the second operation mode, which is the constant height mode, is preferred. In this mode, the probe is scanning the sample at a fixed height in *z*-plane. For both modes, a displacement sensor capable of nano-scale resolution is needed. Capacitive displacement sensors can be used for this purpose. However, the performance of capacitive displacement sensor is limited by several factors in practical implementations, such as stray radiation, electronics-induced noise and geometric effects of the electrodes [1]. These practical concerns impose stringent requirements on the sensor design and calibration.

As an alternative to capacitive sensors, optical displacement sensors based on optical interference are widely used. The sensing performance of optical sensors is limited by counting the interference fringes to measure nanoscale displacement [2]. To improve the optical sensing performance, several research groups have designed the optical displacement sensors by using surface plasmon resonance (SPR) [3]. The SPR based sensors use a monochromatic light source to detect the change in the resonant incident angle at which the reflected optical power reaches the minimum. In these designs, the proposed optical displacement sensors cannot function well when the air gap size is less than 100 nm. This is due to the low efficiency in converting the incident light into the surface plasmon polariton wave on the metal surface. In addition, the resonant incident angle changes only 5 degrees when the air gap is changing from 300 nm to 100 nm. Although a proper design of the layered structure can increase the sensitivity to 0.9 degree per nm [4], the traditional displacement sensor based on SPR using chromatic light source still suffers from low sensing speed since it requires scanning the incident angle.

To overcome this problem, this paper presents a new sensing mechanism, which uses a broadband light to excite SPRs and the displacement is read by measuring the change in the resonant wavelength at a fixed incident angle. The sensing speed of the proposed displacement sensor is improved significantly because we can detect the change of the resonant wavelength by using spectrometer and no scanning process of any parameter is involved.

2 Optical displacement sensor based on surface plasmon resonance excited by broadband light source

Figure 1 presents the proposed structure for the optical displacement sensor based on SPR excited by a broadband light source. The whole setup consists of four different media, which are prism, metal, air, and fiber. They are denoted as Medium 1, Medium 2, Medium 3, and Medium 4 respectively. The dielectric constant ε_i and the refractive index n_i are related by $\varepsilon_i = n_i^2$ for a non-magnetic material [4]. The excitation of surface plasmon is based on Kretschmann-Reather configuration. The incident angle is θ and the incident field is p-polarized. The spectrum of the reflected optical beam is measured in the prism region. In addition, the air gap width L_3 denotes the displacement to be measured.

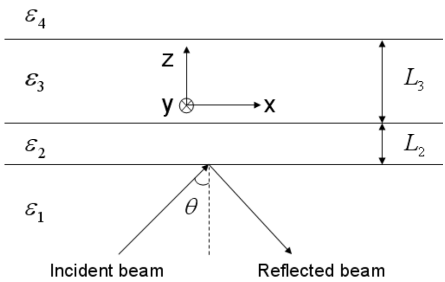

Figure 1: Proposed structure for the optical displacement sensor.

Figure 2 presents the effect of the displacement on the reflected spectrum by using Fresnel's equation. In the calculation, the refractive index of the prism, air and fiber are assumed to be $n_1 = 2$, $n_3 = 1$ and $n_4 = 1.45$ respectively. In addition, the second medium is assumed to be gold.

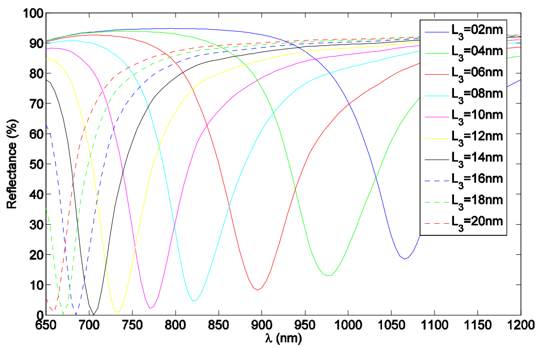

Figure 2: Effect of displacement on the reflected spectrum.

There are several conclusions from Figure 2. Firstly, for a given displacement, there is one wavelength missing on the reflected spectrum. It is due to the conversion of the incident optical field into the surface plasmon polariton wave, which is propagating at the metal-air interface. We can define this wavelength as the resonant wavelength, which is denoted by λ_R. Secondly, when the displacement is increasing, the resonant wavelength λ_R is decreasing. For example, when the displacement is changed from

2 nm to 4 nm, the resonant wavelength is shifted about 90 nm. The reason is that when the displacement is increasing, the effective dielectric constant for the medium above metal surface is decreasing. The resonant wavelength λ_R needs to be smaller in order to compensate the smaller effective dielectric constant. Furthermore, the relationship between the resonant wavelength and the displacement can be derived from the SPR condition [5], which can be expressed as:

$$L_3 = -\frac{\lambda_R}{4\pi\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_3}} \ln\{[\frac{\frac{\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_3}}{\varepsilon_3} + \frac{\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_2(\lambda_R)}}{\varepsilon_2(\lambda_R)}}{\frac{\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_3}}{\varepsilon_3} - \frac{\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_2(\lambda_R)}}{\varepsilon_2(\lambda_R)}}][\frac{\frac{\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_3}}{\varepsilon_3} + \frac{\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_4}}{\varepsilon_4}}{\frac{\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_3}}{\varepsilon_3} - \frac{\sqrt{\varepsilon_1 \sin^2\theta - \varepsilon_4}}{\varepsilon_4}}]\}. \quad (1)$$

3 Conclusions

This paper presents an optical displacement sensor based on SPR which is excited by a broadband light source. At a fixed incident angle, the displacement can be measured from the resonant wavelength. The proposed displacement sensor has a faster sensing speed compared to the displacement SPR sensors that are based on monochromatic light source. It is also shown that the proposed displacement sensor can achieve a high sensitivity. This is evident that the resonant wavelength can be shifted by 45 nm in the reflected spectrum when the displacement is changed by 1 nm.

References:

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