Optics and Laser Technology 94 (2017) 248–252

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Young's modulus measurement based on surface plasmon resonance

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ARTICLE INFO

Article history:
Received 21 August 2016
Accepted 3 April 2017

Keywords:
Surface plasmon resonance
Young's modulus
Pressure sensor

ABSTRACT

In this paper, Young's modulus of polymers is experimentally measured using pressure sensors based on surface plasmon polariton. Theoretical relationships of changes in polymer reflective index due to applying pressure are investigated as well as the dependence of surface plasmon to the polymer reflective index. For the purpose of investigating the effects of the layers thicknesses, numerical simulation is performed using transfer matrix. Changes in resonance angle of surface plasmon due to applying pressure are experimentally studied as well. Practically, a sample of silicon rubber, as one of the most widely-used polymers, is checked and its Young's modulus is measured as 8.1 MPa.

1. Introduction

Over the last few years, using surface plasmon has received a great deal of attention because of its high accuracy, real-time measurement, and easy access [1–4]. It has been used in different fields for different purposes, such as medical, biological and industrial applications [5–7]. Determining the existing material in biological productions, measuring and determining material concentration, industrial functions including optical modulators and gas detection sensors are some examples of its functions [8–10].

Measuring physical parameters of materials plays a key role in designing mechanical parts and in studying the strength of the material. Measuring some parameters including Young's modulus of polymers is one of the most important elements in modern designs [11]. Determining the Young's modulus of polymers thin layers is very significant in MEMS structures, bio-sensors, and bio-structures [13]. For example, determining the Young's modulus of flexible membrane used in artificial tissues has a very important role in the function of bio-sensors and bio-robots [12–15].

There are a number of ways for measuring Young's modulus. One of the most common ones is probe indentation technique which involves nano-indentation and AFM methods, both of which are dependent on material deformation due to applying pressure. Nano-indentation is one of the earliest methods used in order to determine Young's modulus which is applicable on the material in plastic state [16]. AFM, however, is used for the material in elastic state. In AFM method, Young's modulus can be measured by applying atomic force and monitoring deformation changes of the polymer. Derjaguin-Muller-Toporov (DMT) [17] and Johnson-Kendal-Roberts (JKR) are the models introduced for AFM to measure Young's modulus [18].

Pressure sensors have been used for many years. Their mechanism is to convert pressure to measurable parameters like mechanical and electronic signals. Over the last few decades, optical pressure sensors have gained a tremendous attention toward themselves. One of the benefits of these sensors as opposed to other ones is that they are capable of measuring pressure over long-distance. Another advantage is that noise cannot electromagnetically affect them. Using some electro-optical instruments in optical pressure sensors can lead to increasing the accuracy and the sensitivity of the sensors. Optical fibers and brag grating are examples of these instruments [19].

Surface plasmon polariton sensors are based on excitation of free electron oscillations in the interface of metal-dielectric. The excitation of these oscillations is done through employing disappearing optical field with TM polarization [20]. For this purpose, various structures have been proposed so far. Otto and Kretschmann configuration are two famous ones. In this study, we use Kretschmann configuration duo to ease of sample preparation and being easy to use in laboratory setups. In Kretschmann structure, light is entered the prism with TM polarization from different angles. In an angle, which is called resonance angle, phase matching condition is set. Phase matching will lead the light to excite the SPs in the metal/dielectric interface. Angular interrogation is a practical procedure for surface plasmon sensors using Kretschmann configuration. In this method, by measuring of reflectivity for different incident angles, we can plot resonance diagram for our SP structure where in resonance angle there is a dip. The depth and width of the dip will play key roles in efficiency of these sen-

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http://dx.doi.org/10.1016/j.optlastec.2017.04.002
0030-3992/

sors. One of the most important elements in depth and width of the dip is the thickness and the type of metal medium [21–23]. According to the reports, aluminum and copper are considered as metals used less frequently in this case while gold and silver are widely-used metals [24]. Surface plasmon resonance angle is affected by the type of the metal and reflective index of the dielectric. Paying attention to the dependence of surface plasmon resonance to reflective index of dielectric and the dependence of reflective index of some materials to physical parameters like temperature, pressure, and so on will form the idea of pressure sensors based on surface plasmon polariton.

Fig. 1 illustrates Kretschmann configuration for setting pressure sensor up which includes the SF4 prism, silver layer, and the Silicone Rubber polymer as dielectric. Laser beam is introduced to prism with TM polarization from different angles. Applying pressure will cause changes in polymer reflective index which in turn will lead to changes in surface plasmon resonance angle.

In this work, the measurement of Young's modulus for polymers is investigated experimentally and theoretically using pressure sensors based on surface plasmon. First, the theoretical governing rules on pressure sensors based on surface plasmon with angular interrogation are studied. Then, the way of determining Young's modulus is presented using plasmonic pressure sensors. The optimized choice of metal thickness has important effect on the efficiency of the sensors which are based on surface plasmon. In order to optimize the thickness of metal layer and simulation of the pressure sensor function, numerical simulation is done using transformation matrix method. The experimental configuration used here is then presented. Finally, the experimental results are given and discussed.

2. Theory

SPs waves are longitudinal oscillations of free electrons along an interface of dielectric and metal. As is shown in Fig. 1, when incident light has TM polarization due to attenuated total reflection at a critical angle (resonance angle), the incident light will excite the surface plasmon polaritons. Such polaritons will be coupled into and propagate at the metal/dielectric interface [25].

Surface plasmon polariton sensors act based on the dependence of surface plasmonresonance to dielectric refractive index. With Considering Kretschmann configuration and angular interrogation, resonance angle is dependent on dielectric reflective index around the metal. If the metal is surrounded by a polymer with Young's modulus as E_p, applying pressure can change the density which in turn can change reflective index of the environment around the sensor. This could be seen as a change in resonance angle [26]. Density changes due to applying pressure are obtained through relationship (1):

$$\delta\rho = -\rho\frac{V}{V-V_f}\frac{\delta l}{l} = -\frac{\rho}{v_p}\varepsilon \tag{1}$$

where v_p represents the relative volume whose value is considered 1 for polymers. ρ is the polymer's density. Axial strain ε is calculated by the following equation:

$$\varepsilon = \frac{-\Delta p}{E_p} \tag{2}$$

Therefore, density changes could be stated in terms of pressure changes as stated in relationship (3):

$$\frac{\partial\rho}{\partial p} = \frac{\rho}{E_p} \tag{3}$$

Employing (3), and using some mathematical manipulation for reflective index changes in terms of pressure changes, it is concluded:

$$\frac{\partial n}{\partial p} = \frac{\partial n}{\partial\rho}\frac{\partial\rho}{\partial p} = \left(\rho\frac{\partial n}{\partial\rho}\right)\frac{1}{E_p} \tag{4}$$

In constant temperature and wavelength, for polymers [27]:

$$\left(\rho\frac{\partial n}{\partial\rho}\right)_T \approx 0.50 \tag{5}$$

Since resonance angle changes are dependent on reflective index changes, it is concluded that pressure changes will change resonance angle:

$$\frac{\Delta\theta_{res}}{\Delta P} = \frac{\partial\theta_{res}}{\partial n_P}\frac{\partial n_p}{\partial P} = \frac{\partial\theta_{res}}{\partial n_P}\cdot\left(\rho\frac{\partial n}{\partial\rho}\right)_T\frac{1}{E_p} \tag{6}$$

In above-mentioned equation, resonance angle changes in terms of reflective index changes are constant. Considering (5) and (6), it is seen that if pressure is applied on a polymer with indefinite Young's modulus, it could be calculated through resonance angle changes with high accuracy. Relationship (7) is used to measure the Young's modulus.

$$E_p = 0.5\frac{A}{B} \tag{7}$$

In which A is resonance angle changes due to reflective index changes, which has a constant amount for each plasmonic structure, and B is resonance angle changes due to applying pressure.

In producing of surface plasmon polaritons condition based on theories the penetration depth of the field into the dielectric is typically on the order of λ/2 of the wavelength in the medium, whereas in the metal it is characteristically given by the skin effect. [20]. It, however, could be determined accurately using wave number. Penetration depth has a significant role in determining the minimum thickness of polymers whose Young's modulus can be measured by the kind of configuration.

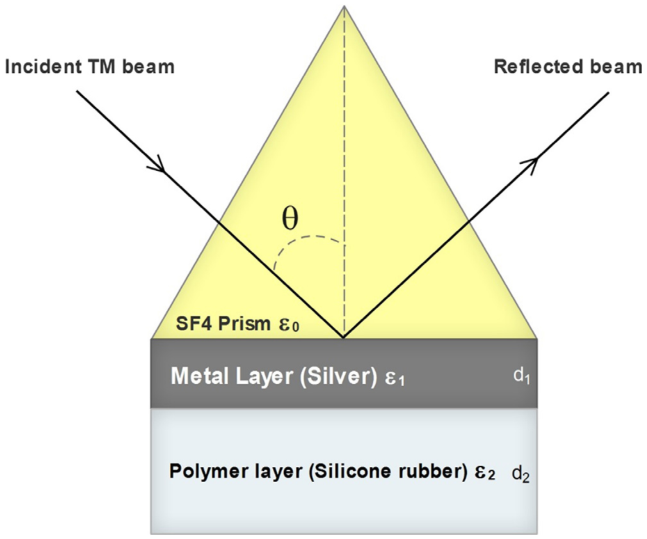

Fig. 1. Scheme of surface plasmon resonance structure (SF4Silver-Sillicon rubber).

3. Simulation and design

For the purpose of investigating the effects of the polymer layer in the system utilization, as shown in Fig. 1 SF4 prism, silver and silicone rubber polymer are considered as layers 0, 1 and 2 respectively for transfer matrix method [4].

The refractive indices of used materials in simulation are assumed as follows: $n_0 = 1.7496$, $n_1 = 0.157 + i3.08$, $n_2 = 1.39$. The