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Size effect of optical silica microsphere pressure sensors

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ABSTRACT

Two types of optical pressure sensors with silica microspheres are proposed. The size effect of optical silica microsphere pressure sensors is studied by using a single-wavelength laser beam and polarimeters. The silica microspheres with diameters of 1.0 μm, 1.5 μm and 2.0 μm are prepared on garnet substrates by a self-assembly method. The pressure and the optical properties of the silica microspheres are measured by a resistance strain sensor and Thorlabs Stokes polarimeters as a function of the external direct current (DC) voltage. The optical silica microsphere sensor in transmission mode is suitable for pressure measuring. The results show that the pressure increases, while the diameter of the silica microspheres decreases. The maximum internal pressure can reach up to 7.3×10^7 Pa when the diameter of the silica microspheres is 1.0 μm.

1. Introduction

Silica microspheres can be used as a key component of optical sensors, because of their high sensitivity, wide dynamic range measurement, repeatability and electromagnetic insensitivity [1–3]. The physical properties of the silica microspheres have been extensively researched, such as the optical polarization properties [4,5], temperature effect [6], laser coupling and transport properties [7–9]. The preparation technology of silica microspheres, splicing technology, broad light source and optical spectrum analyzer are sometimes difficult to satisfy. The physical properties of a light source can be changed, when the light interacts with the silica microspheres, especially when the silica microspheres are deformed by an external force. The Raman effect of the individual microsphere is determined for changes in the size of the microspheres [10,11]. The size effect of silica microspheres as strain or pressure sensors has seldom been researched.

In this letter, two types of optical pressure sensors with silica microspheres (its diameter is 5 μm) are proposed. Optical silica microsphere pressure sensors with different diameters are researched by using a single-wavelength laser beam and Stokes polarimeters in transmission mode. A single-mode optical fiber laser with a wavelength of 1550 nm and Thorlabs PAX 5710IR3 polarimeters are used as a light source and optical polarization properties detector, respectively. The silica microspheres with diameters of 1.0 μm, 1.5 μm and 2.0 μm are prepared on garnet substrates by a self-assembly method. The linearly polarized laser beam passes through the silica microspheres in the direction perpendicular to the plane of the glass plate. The stress and pressure distribution of the silica microspheres with different diameters are analyzed and calculated through elastic mechanics. The surface morphology of the silica microspheres with different diameters and the pressure generated by the effect of the garnet–graphite interface are measured by an optical microscope and a resistance strain sensor, respectively. The optical polarization properties of the laser beam, which passes through the different samples, are also measured.

2. Experimental setup

2.1. Morphology measurement

The surface morphology and the relative size change of the silica microspheres with different diameters of 1 μm, 1.5 μm, and 2.0 μm are observed by an XPH-300 Optical Microscope with a 10X eyepiece and a 60X/0.75 objective lens in reflection mode in the same experimental conditions.

2.2. Polarization, transmittance and reflectivity measurement

Fig. 1(a) presents the schematic view of our experimental set-up in a transmission mode. A near infrared single-mode fiber laser with a wavelength of 1550 nm and a power of 18 mW, is used as an optical source in this experiment. The silica microspheres with a diameter of 5 μm are prepared on garnet substrate ($2 \times 2 \times 0.39$ mm), from alcohol suspensions by a self-assembly method [12]. A pair of copper electrodes

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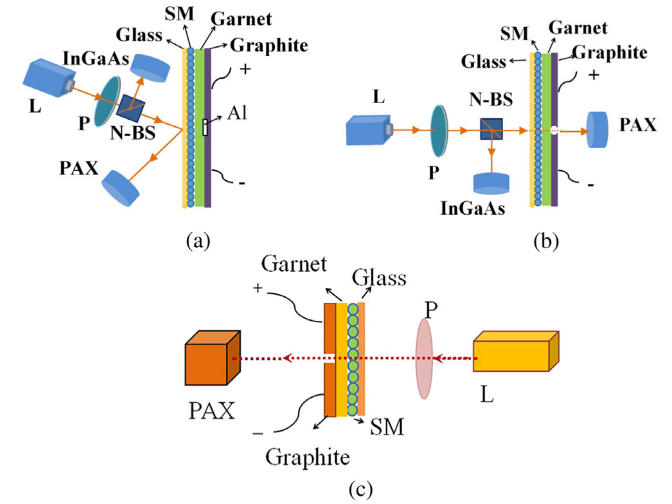

Fig. 1. Schematic of the experimental setup. (a) Transmission mode, (b) Reflection mode, (c) Measuring mode. L — Laser, P — LPNIR 100 Polarizer, SM — Silica microspheres, PAX — PAX 5710IR3 polarimeter, Glass — Glass plate, N-BS — 50:50 Non polarization beam splitter, Al — Aluminum film.

are in contact with graphite at a distance of 1 mm. A round hole with a diameter of 1 mm is punched in the center of the graphite. The near infrared laser beam propagates in polarization maintaining fiber, goes through the LPNIR 100 polarizer and is changed into a linearly polarized laser beam, reaches at the CM1-BS015 non-polarizing 50:50 beam splitter and be divided into two parts. One part of the laser beam arrives at the InGaAs detector. The other part of the laser beam goes through the glass, silica microspheres, garnet, the hole of graphite and arrives at the PAX 5710IR3 polarimeter. The InGaAs detector and PAX 5710IR3 polarimeter are used to detect the optical power of the laser beam. The external DC power supply is connected to the graphite.

Fig. 1(b) presents the experimental setup in reflection mode. An Al film with a diameter of 1 mm and a thickness of 5 μm is prepared on one side of the garnet substrate by a magnetron sputtering method, and the silica microspheres (its diameter is 5 μm) are prepared on the other side of the garnet substrate by a self-assembly method. The graphite with a round hole (its diameter is 1 mm) is fixed on the Al film. The external DC power supply is connected to the graphite. The laser beam reflects from the Al film and arrives at the polarimeter. The transmittance and the reflectivity of the linearly polarized laser beam can be obtained from the ratio of the above laser power.

Fig. 1(c) presents the scheme of our experimental setup. A single-mode optical fiber laser with a wavelength of 1550 nm and a power of 18 mW, is used as a light source in this experiment. The silica microspheres with different diameters of 1 μm, 1.5 μm, and 2.0 μm are prepared on garnet substrates ($2 \times 2 \times 0.39$ mm) by a self-assembly method [13]. A pair of copper electrodes are in contact with graphite, and the distance between them is 1 mm. A round hole with a diameter of 1 mm is punched in the center of the graphite. The laser beam propagates in a polarization maintaining fiber, which passes through the LPNIR 100 polarizer and is changed into a linearly polarized light, passes through the glass plate, silica microspheres, garnet, the hole of graphite in the perpendicular direction and arrives at the PAX 5710IR3 polarimeters. The polarization properties of the laser beam, which interacts with the silica microspheres, can be obtained from the PAX 5710IR3 polarimeter. The external DC power supply is connected to the graphite.

2.3. Pressure measurement

The glass plate, silica microspheres with different diameters, garnet with the same size, graphite and pair of copper electrodes are integrated by mechanical force. The stress can be measured by an RFP-604 resistance strain sensor, and the pressure can be calculated by the division of the stress and area of the garnet, when the external DC voltage changes from 0 V to 1.7 V, using a similar method from the literature [13,14].

3. Theory

To realize the mechanical properties of the optical silica microspheres sensor, the relationship between the stress and the radius of the silica microspheres is analyzed. The stress representation of the silica microspheres can be found from Fig. 2.

The elastic stress of the silica microsphere can be described by Hooke's law,

$$F_{\text{elastic}} = \kappa(R_0 - R) \tag{1}$$

F_{elastic} is the stress of the elastic silica microspheres, κ is the elasticity coefficient of the silica microspheres, R is the radius of the silica microspheres at the initial state, and R_0 is the radius of the silica microspheres at the end state.

S is the projected area of the silica microspheres on garnet.

$$S = \pi R^2 \tag{2}$$

$$F_{\text{silica, external}} = P_{\text{silica}} \times \pi R^2 \tag{3}$$

$F_{\text{silica, external}}$, and P_{silica} are the external stress and pressure generated from interface effect of garnet and graphite at the initial state, respectively.

$$F_{\text{silica, internal}} = P_{\text{silica}} \times \pi R^2 + F_{\text{elastic}} \tag{4}$$

$F_{\text{silica, internal}}$ is the internal stress generated from the silica microspheres.

$$F_{\text{silica, internal}} = P_{\text{silica}} \times \pi R^2 + \kappa(R_0 - R) \tag{5}$$

$P_{\text{silica, internal}}$ is the internal pressure generated from the silica microspheres. The relationship between $P_{\text{silica, internal}}$ and the radius of the silica microspheres can be obtained from the following equation,

$$P_{\text{silica, internal}} = \frac{F_{\text{silica, internal}}}{S} = P_{silica} + \frac{\kappa}{\pi}\left(\frac{R_0 - R}{R^2}\right) \tag{6}$$

The P_{silica} of the silica microspheres with different radius are basically the same, and the change in pressure as a function of the external DC voltage can be obtained from the derivative of the pressure.

$$\frac{dP_{\text{silica, internal}}}{dR} = \frac{\kappa}{\pi}\left(\frac{R - 2R_0}{R^3}\right) < 0 \tag{7}$$

4. Results and discussions

4.1. Morphology measurement

The surface morphology of the silica microspheres can be obtained from the same experimental conditions. Fig. 3(a)–(d) present the change in silica microspheres with different diameters. The surface morphology of the silica microspheres becomes obvious, because of the optical diffraction limit of the optical microsphere is determined by the wavelength of the light source and the numerical aperture of the objective lens. The silica microsphere is easy to observe when the radii of the silica microspheres increases, especially when it is higher than the optical diffraction limit. The Fig. 3(a)–(d) show that the silica microspheres present a random and assembly distribution. It is only need to pay attention to the diameters of the silica microspheres, instead of their distribution. This is very helpful for designing and preparing optical devices.

4.2. Transmittance and reflectivity measurement

In order to seek out the relationship between the pressure and the optical properties of the silica microspheres (its diameter is 5 μm), the relationship between laser power ratio (transmittance and reflectivity)