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Readout of the vibration of nanowires using fibre optics: Combining light scattering and the interference effect

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ABSTRACT

Nanowires are good transducers to sense minute mechanical changes. A limitation in the mechanical motion detection of the nanowire is to identify the mode of vibration. In this work, we investigate the nano-optomechanical interaction between a nanowire and a focused Gaussian beam of light to analyze the vibration of nanowires. We combine effects of light scattering and light interference, across the optical axis and along the optical axis of the micro-lens fibre optic interferometer which is used in our study, respectively. Our analysis shows that the optimal detection sensitivity of the micro-lens fibre optic interferometer depends on both the vibration direction and diameter of the nanowire. Quantities which are of interest for experimentalist are analyzed, and our results could provide a guide for optical readout experiments of the vibration of nanowires.

1. Introduction

In the continuous development of applications of nanomechanical systems, nanowires represent one class of typical structures and materials. Nanowire characteristics and applications have attracted research extensive attention, wherein the detection of nanowire motion is an current important challenge. Successfully detecting nanowire vibration remains one of the critical technological challenges to their use as mechanical sensors. Detecting nanowire vibration and using nanowires as elements to sense micro-/mesodisplacement have potential engineering applications ranging from mass detection [1] to force transduction [2]. A current effective and practical method to investigate the motion characteristics of nanowires is optical detection, including interferometric techniques [3–11] and laser-deflection [12–16] or light-scattering [17,18] methods. A challenging limitation of these detection methods is to achieve bidimensional motion measurement in a given system. And some other researches [19–21] have been proposed to overcome the limitation of detecting only a single motion dimension in a specific system. In this paper, we adopt a method that can realize motion detection of a nanowire with an arbitrary direction of vibration in a two-dimensional plane, and find the corresponding optimal working points where the maximum detection sensitivity is in. Our scheme includes both light scattering and light interference [18] to accomplish the detection in a given system.

2. Vibration detection principles using micro-lens fibre optics

In our study, micro-lens fibre optic interferometry plays a vital role in the procedure to measure the vibration of a nanowire vibrating in a two-dimensional plane. Fig. 1 displays the related fundamental physics principles. At the fibre/ambient interface, a part of the incident laser light is reflected and propagates in the opposite direction, and the transmitted light is expanded, collimated and focused on the suspended nanowire in the form of a converged Gaussian beam. The wavelength of the incident laser light is 1.55 μm, and the power of the laser coupled into the fibre is 62.5 μW. The fibre (Thorlab, PM1550-XP) has the numerical aperture (NA) 0.125 and the refractive index 1.44938. The system can work in the air environment whose refractive index is 1.0003. Light arriving at the surface of the nanowire is scattered. Some of the scattered light from the nanowire is collected to return to the fibre and interfere at a photodiode with light reflected from the end of the fibre. In the system, two thin lenses labelled as Lens1 (Lightpath 354430) and Lens2 are placed in sequence. The numerical aperture, the focal length, the working distance and the out diameter of Lens1 and Lens 2 are 0.15, 5 mm, 4.37 mm and 2 mm, respectively. Along the incident light propagation direction, the mode field diameter of the optic fibre is 10 μm; the distance

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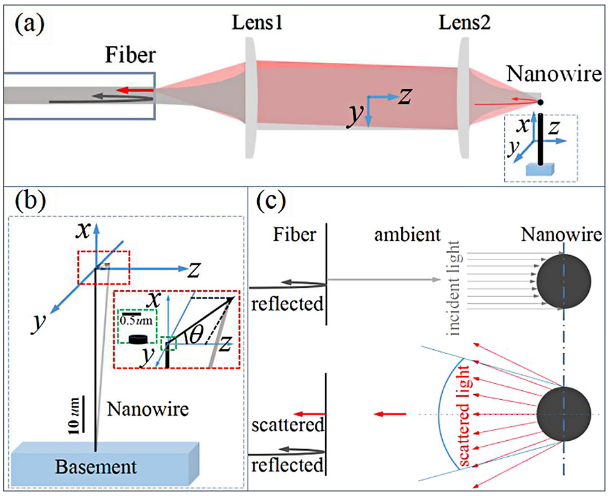

Fig. 1. (Colour online.) (a) Sketch of the light propagation path. The incident light with the propagation direction from the fibre to the nanowire is represented by the grey Gaussian shape. The backward scattered light represented by the red colour one is along the opposite direction. (b) Figure illustrating the concept of vectorial vibrations of flexural modes of a vibrating nanowire. A vibration vector with a random direction can be decomposed into two components along the y and z directions. θ is the vibration angle, the angle between the vibration vector and z axis positive direction. (c) Fabry–Perot cavity whose walls are formed by the end of the fibre and the surface of the nanowire. The black disc is the cross-section of the nanowire. The range between the two blue lines is used to indicate the range of the aperture angle.

from the end of the fibre to the Lens1 is 4.37 mm. The distance between the two thin lenses is 4 mm; the distance from Lens2 to the nanowire is 4.37 mm; and the radius of the focused light spot is 5 µm. The nanowire used here is an silicon nanowire whose refractive index appears to be 3.47, and the typical radius of the nanowire we use to analyze the nanomechanical vibration is 0.26 µm. In this paper, we use Mie scattering theory to analyze the scattered light because the size of the nanowire and the wavelength of the incident light are comparable, which can result in Mie scattering [22].

The direction of vibration of the nanowire may be arbitrary in the two-dimensional plane, but it can be decomposed into two definite directions that are mutually perpendicular [19]. Here, the two-dimensional plane refers to the yz coordinate plane, and the two orientations shown in Fig. 1 are defined as being along the y axis and the z axis, representing in-plane and out-of-plane vibration, respectively. The light signal detected by the detector varies either when the nanowire has an out-of-plane or an in-plane vibration. This is because motion along the incident light propagation direction can alter the interference light and motion along the direction across the light spot can alter the scattered light. Notably, we present the concept of the backward and the forward scattered light. When the intersection angle between the direction vector of the scattered light and the incident light is less than 90°, we call it forward scattered light; when the angle is greater than 90°, we call it backward scattered light.

Both the light reflected from the end of the fibre (E_{0r}) and that scattered from the nanowire contribute to the light collected at the photodiode. The light signal forming on our detector is

$$I_t \propto |E_{0r}|^2 + |E_s|^2 + 2Re\{E_{0r}E_s\} \tag{1}$$

If E_0 is the laser light field coupled in the fibre, then $E_{0r} = aE_0$ (amplitude reflectivity a) resulting from Fresnel reflection at the fibre/ambient interface. E_s is the fraction of the scattered light that can be collected by the lenses and the fibre, collectively, and can be expressed by the following equation

$$E_s \propto |\int_{NA} d\psi \exp(-ik(R+z+|\vec{r}|cos\theta)) \exp(-\frac{(y+|\vec{r}|sin\theta)^2}{\omega_{0s}^2}) \times \sqrt{\frac{2}{\pi k r_d}} \exp(-ikr_d)T(\psi)|. \tag{2}$$

Here, the scattering angle is expressed by ψ, and notably, only the light within the range of the numerical apertures (NAs) can be guided back into the optical fibre. R is the length from the origin of the coordinate system to the end surface of the optical fibre. $\vec{r}$ is the two-dimensional vibration amplitude at the equilibrium point, and θ is the angle between vector $\vec{r}$ and the z-axis positive direction, which is marked in Fig. 1(b). ω_{0s} characterizes the waist of the converged Gaussian beam focused on the surface of the nanowire, and r_d is the scattering distance used to describe the interval between the central axis of the nanowire and the points of the scattering field. k represents the wave number (WN) in the ambient environment. In the equation, y and z are the nanowire position deviations from the coordinate origin in the y and z directions, respectively. When the nanowire reaches a position (y_0, z_0) in the yz plane, we call it the position equilibrium point. Then, the scattered field is $E_s \propto |\int_{NA} d\psi \exp(-ik(R+z_0+|\vec{r}|cos\theta)) \exp(-\frac{(y_0+|\vec{r}|sin\theta)^2}{\omega_{0s}^2})\sqrt{\frac{2}{\pi k r_d}} \exp(-ikr_d)T(\psi)|$. A small amplitude vibration occurs to the nanowire that is located at the equilibrium point, and the direction of the vibration vector $\vec{r}$ of the nanowire is random and may not lie exactly in the z direction or y direction. The projections $|\vec{r}|cos\theta$ and $|\vec{r}|sin\theta$ are the amplitudes along the z and y axis directions, respectively. Moreover, $T(\psi)$ is called the scattering matrix and meets the relationship $T(\psi) = \sum_{n=-\infty}^{\infty} b_n \exp(in\psi)$. Here, b_n is the scattering coefficient and depends on both the radius of the nanowire r_s and the relative refractive index m_s, where $m_s = n_s/n_m$ for the ratio of the nanowire refractive index n_s and that of the ambient medium n_m. Furthermore, the relationship between b_n and m_s as well as r_s can be expressed as $b_n = \frac{m_s J_n'(m_s kr_s) J_n(kr_s) - J_n(m_s kr_s) J_n'(kr_s)}{m_s J_n'(m_s kr_s) H_n(kr_s) - J_n(m_s kr_s) H_n'(kr_s)}$ [22,23], where J_n and J_n' are the Bessel function of the first kind and its first order derivation. H_n is the Hankel function. Notably, we analysis the far-field scattering, then we simulate the electric field outside and far from the nanowire. But, I would like to emphasize that the Maxwell boundary condition is adopted to calculate the scattering coefficient, so the electromagnetic modes both inside and outside the silicon nanowire should be taken into consideration in the calculation process of the scattering coefficient b_n. Finally, Eq. (2) shows that vibration in the z direction has an effect on the phase rather than the scattered light intensity, namely, the nanowire vibration in the z direction can only change the interference light. Conversely, monitoring the interference light can cause a vibration in the z direction [24]. However, the vibration in the y direction can modulate of the intensity of the scattered light. Given a specific set of micro-lens optics (wave length, NAs, relative refractive index, etc.) and nanowire radius, the scattered field E_s is a function of θ, y and z, that is, the vibration direction and the position in the yz plane. Accordingly, the combined light signal I_t forming on the detector, which is after the light scattering and the light interference, is also a function of θ, y and z.

Identifying the vibration with a random direction in the two-dimensional plane (the yz coordinate plane) as well as the corresponding vibration conversion efficiency coefficients, which converts the unit amplitude vibration of the nanowire into the output signal, to obtain the maximum detection sensitivity from the nanowire vibration is a significant part of our study. In our theoretical calculation, the output signal is the optical power which is in unit of watt W. From the definition of the conversion effi-