Study on silicon micro-resonators by using a novel optical excitation and detection apparatus

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A novel optical excitation and detection apparatus was used to investigate the characteristics of silicon micro-resonators, which was activated into vibration by a laser beam irradiation. The beam diameter of the excitation light was less than 10 μm. The vibration amplitude of the resonator was detected by the interferometer with high resolution of 0.1 nm and measurement repeatability of less than 3 nm. The resonant frequency of the micro-resonator was obtained to be 8.75 kHz with full-width at half-maximum (FWHM) of 0.18 kHz. It is shown that the method is useful and reliable for measuring micro-displacement and micro-vibration of minute objects with nanometer accuracy.

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With the development of micro-electro-mechanical system (MEMS), silicon micro-resonators are considered as a basic and very useful element. Sensors based on the silicon micro-resonator have many advantages such as high sensitivity, low cost, and small size[1−3]. There have been publications on interferometric measurement and laser beam excitation method in silicon micro-resonators[3−5]. But the resolution and precision still need to be improved. In this paper, we report the measurement results of a silicon micro-resonator by using an optical excitation and detection apparatus with sub-nanometer resolution and nanometer repeatability.

The measurement system used in this work is shown schematically in Fig. 1. It is composed of an excitation unit and a measurement unit. In the excitation unit, the light emitting from the laser diode LD1 was directed onto the surface of the device under test, which was a tiny cantilever made of silicon in the experiment. A part of light energy will be absorbed by the irradiated beam and convert into heat, resulting in the non-uniform temperature increase and the deformation of the beam. If the intensity of LD1 is modulated periodically, the beam will vibrate accordingly. The beam has its mechanical resonant frequency, which may depend on some environment conditions. It is the task of this work to measure behaviors of its resonance. There have been some papers to analyze the micro-resonator. Fatah[1] presented a model to describe a silicon bridge micromechanical resonator in optical activation. Liu *et al.* took a bi-metallic effect into consideration, and revised Fatah's model[6]. Later they reported an experimental study on a silicon cantilever micro-resonator[7]. Kim *et al.* presented a model for static deformation of a silicon cantilever under laser irradiation[4]. There are some common conclusions for the micro-resonator, that is, the resonant frequency f_{r} is a function of beam length L, thickness t, density ρ, and Young's module E of the material

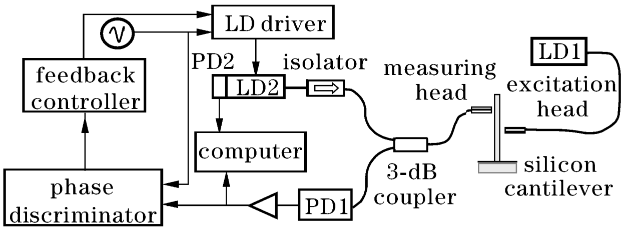

Fig. 1. Measurement system of the resonant frequency of a micro-cantilever.

$$f_{\mathrm{r}} \propto \frac{t}{L^2}\sqrt{\frac{E}{\rho}}. \tag{1}$$

The vibration amplitude is a function of the absorbed laser power, thermal expansion coefficient, heat conductivity, and specific heat of the material, as well as of ρ and E. The relationship of these parameters is quite complicated and depends on the device structure, heat dissipation condition, and other factors. Detailed measurement of the characteristics of micro-resonator is very helpful for understanding the mechanisms and verifying the proposed models.

The measurement unit in Fig. 1 is a LD fiber-optic Fizeau interferometer, which is used to measure the amplitude and resonant frequency of micro-resonator. In the interferometer, the light emitting from LD2 passes an isolator and a 3-dB fiber coupler, and then outputs from end face of the measurement head. Some of the light reflected from surface of the tested cantilever will be coupled back into the measurement head, which will interfere with the light reflected directly from the end face of the measurement head and detected by a photodiode PD1. The amplified output signal of PD1 is digitized by an A/D converter and processed by a computer[8−10].

To demodulate the interference signal with high precision and low noise, LD2 is modulated by varying its injection current. The injection current consists of a direct current (DC) component i_0 and a sinusoidal-modulation component of $\Delta i\left(t\right) = i_1 \cos\omega_{\mathrm{c}}t$. Accordingly the wavelength of LD2 will be modulated too, and can be expressed as

$$\lambda\left(t\right) = \lambda_0 + \beta\Delta i\left(t\right), \tag{2}$$

where λ_0 is the central wavelength of LD2, β is the modulation coefficient of the wavelength. The interference signal detected by PD1 is

$$S(t) \propto \cos\left[z\cos\left(\omega_c t+\theta\right)+\alpha\right], \tag{3}$$

where $z = 2\pi\beta i_1 l_0/\lambda_0^2$, $\alpha(t) = 4\pi r(t)/\lambda_0$, l_0 is the optical path between objective and reference waves when the tested object is static, $r(t)$ is the displacement of the tested object, which is the main measured parameter; θ stands for the phase difference between the modulation and the cantilever vibration. When the interference signal is collected by the computer, the displacement can be obtained through the Fourier transform of Eq. (3)[8].

The injection current modulation can change the wavelength of LD2, but the output power will be modulated also, which will add a false signal to the interference. To avoid this influence the monitor photodiode PD2 inside LD2 package is used to measure the intensity change. After modifying the interference signal by using the PD2 signal, the measurement errors caused by the intensity modulation can be efficiently eliminated.

A phase discriminator and a feedback controller, as shown in Fig. 1, are used to reduce and eliminate external disturbance and to enhance the measurement precision and repeatability. The injection current from the laser driver will be modified by output of the feedback controller. This design can efficiently eliminate the external disturbance by adjusting the injection current of LD2[11].

In the experiment, the specimens were silicon micro-cantilevers with length of 1 mm, width of 300 μm, and thickness of 10 μm. The excitation source LD1 was a 785-nm laser diode with the output power of 10 mW, which was driven by an alternative current (AC) synchronized with a signal generator. The diameter of excitation laser beam was about 10 μm. The vibration amplitude could be measured with modulation frequency variation. Figure 2 shows the frequency response of the specimen No. 1 (Si/SiO$_2$/Al). The surface of the cantilever beam was coated by an aluminum film. It was shown that resonance occurred at 8.75 kHz; the full-width at half-maximum (FWHM) of the resonance curve was 0.18 kHz, indicating a Q value (the quality factor of the resonance) of 48.6. Other cantilever specimens were also measured with different resonant frequencies, for example, 19.75 kHz for specimen No. 2 (Si), and 21.15 kHz for specimen No. 3 (Si/SiO$_2$).

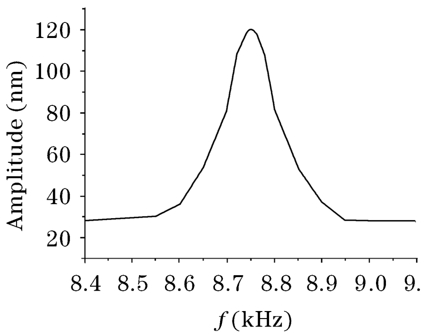

Fig. 2. Frequency response of optically excited micro-cantilever.

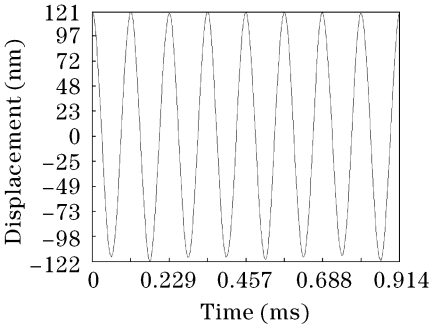

Fig. 3. Displacement curve of the micro-cantilever No. 1 at resonance.

The vibration amplitudes of the cantilever specimens at resonance were usually in the range of several hundreds nanometers. Figure 3 shows a measured curve of cantilever specimen No. 1 at resonance. The data have been calibrated in nanometers by the National Center of Measurement and Test for East China. And a theoretical analysis of measurement accuracy in sinusoidal phase modulating interferometry was presented[12]. The mean measurement value of vibration amplitudes is 119.51 nm.

In conclusion, vibration characteristics of silicon cantilever micro-resonators were investigated by laser excitation and a high precision fiber-optic Fizeau interferometer. Experimental results have shown that the resolution of the measurement can reach to 0.1 nm, and the repeatability for the displacement measurement is better than 3 nm. The apparatus has passed the inspection performed by the National Center of Measurement and Test for East China. It can be used to measure mechanical and dynamic characteristics of other objects, especially of micro devices.

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References

1. R. M. A. Fatah, Sensors and Actuators A **33,** 229 (1992).
2. D. Uttamchandani, Z. N. Li, L. M. Zhang, and B. Culshaw, Optical and Laser in Engineering **16,** 119 (1992).
3. Z. Fang, G. Chen, R. Qu, H. Zhao, and H. Ding, Infrared and Laser Engineering (in Chinese) **28,** (2) 49 (1999).
4. B. H. Kim, F. E. Prins, D. P. Kern, S. Raible, and U. Weimar, Sensors and Actuators B **78,** 12 (2001).
5. T. Kobayashi, J. Ohsawa, T. Hara, and N. Yamaguchi, Jpn. J. Appl. Phys. **43,** 1178 (2004).
6. Y. Liu, W. Tian, J. Liu, and S. Zhang, Acta Photon. Sin. (in Chinese) **32,** 1216 (2003).
7. Y. Liu, J. Liu, and S. Zhang, Acta Opt. Sin. (in Chinese) **23,** 529 (2003).
8. O. Sasaki and H. Okazaki, Appl. Opt. **25,** 3137 (1986).
9. X. Wang, X. Wang, Y. Liu, C. Zhang, and D. Yu, Opt. Laser Technol. **35,** 219 (2003).
10. D. Li, X. Wang, and Y. Liu, Chin. Opt. Lett. **2,** 328 (2004).
11. T. Suzuki, O. Sasaki, K. Higuchi, and T. Maruyama, Appl. Opt. **28,** 5270 (1989).
12. O. Sasaki and H. Okazaki, Appl. Opt. **25,** 3152 (1986).