

Laser self-mixing interferometer for MEMS dynamic measurement

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Abstract Laser self-mixing interferometer has the advantages of simple architecture, compact size, naturally self-aligned optical characteristics, and low cost. It is promising to replace conventional interferometers for physical measurements, such as displacement, distance, velocity, vibration, and so on. In this paper, this interferometer was tried to be used for micro-electro-mechanical system (MEMS) dynamic measurement. Firstly, its measurement principle based on a three-mirror cavity model was presented, and then the laser self-mixing interferometer for MEMS dynamic measurement was designed, experiments were finally performed as target moves with different forms. Experimental results suggest that self-mixing interferometer is available for MEMS dynamic measurement, and may have wider applications in the future.

Keywords laser self-mixing interferometer, dynamic measurement, micro-electro-mechanical system (MEMS)

1 Introduction

In recent years, a technology of micro-electro-mechanical system (MEMS) has made important progress in basic theory, components design and manufacture, micro systems integration and its applications [1–4]. Due to the lack of effective testing method, there is a long way to go for a wide range of production and large-scale application [1,2]. MEMS test is crucial for its design, simulation, products manufacture, quality control and performance evaluation. The size of MEMS devices in mm to micron [5], and this device was characterized with the property of high frequency and high integration [6]. Therefore, none

optical test method, which always require additional sensors or energy conversion components, usually affects the integrity of microstructure, and mechanical properties resulting in unpredictable error. For example, the electrical method is often used to measure capacitive sensors. When the sensor is bare, the parasitic phenomena play a major role. As a matter of fact, the stray capacitance of the connecting wires and of the external front-end can be an order of magnitude higher than the whole capacitance of the combs (typically, 0.1–0.5 pF), and can often mask the sensor response. Also, with some devices, a large spurious beating between the driving signal and the carrier may be observed at the output. So many authors have proposed optical methods, based, for example, on image processing or diffused light analysis [7–9] to perform a direct noninvasive measurement of the mass movement. Interferometry offers the best accuracy and resolution among optical methods. Unfortunately, classical interferometric schemes are difficult to apply to MEMS characterization for different reasons. First, the vertical side walls of the mass (in the planes x - z and y - z) are hidden by the case and/or silicon frame and cannot be easily reached by a laser beam. Second, the mass does not represent a good optical surface, since it is rough, and holed to remove the underlay sacrificial layer. Finally, the setup should allow measurements inside a vacuum chamber, since it is often required to determine Q as a function of pressure. Besides, optical instruments are usually bulky, complicated, and expensive, for example, Veeco Company's MEMS3500 and MEMS tester wykoNT1100, and American Sandia national laboratory MEMS reliability testing system ShMMer, etc. [10]. Therefore, an efficient solution is provided by feedback interferometry, its main advantage is that it requires neither external optics (other than a collimator and/or a focusing lens), nor accurate alignment and wave front matching. Also, it has no reference arm, and thus it can be implemented by a simple and compact setup [11,12].

In recent years, laser self-mixing interferer has been developed rapidly [13–17]. It has been used for physical properties measurement, such as displacement [11,13,14], distance [15], speed [16], and vibration [17]. Compared with traditional double-beam interferer, laser self-mixing interferometer has many unique advantages: 1) simple and compact structure, durable, easy to miniaturization, low cost; 2) able to realize ‘self alignment’ and ‘self detection’, and convenient to regulate y ; 3) high sensitivity and nano-precision for vibration or displacement measurement; 4) suitable for measurements of weak light and rough surface.

This paper presents laser self-mixing interferometer for MEMS dynamic test. Due to this interferometer endowed with the advantages of simple and compact structure, easy alignment, and low cost, it can be developed a new MEMS dynamic testing system.

2 Methods

2.1 Measurement principle of laser self-mixing interferer

To analyze the self-mixing interference, three-mirror cavity model is used because of its simple and intuitionistic. Figure 1 shows the schematic diagram of a three-mirror cavity model with a solitary semiconductor laser diode (LD), in which laser facets and external reflector form a three-mirror (r_{1-3}) compound cavity. r_1 and r_2 form the laser’s inner cavity, r_3 and the external reflector form the laser’s external cavity. Lengths of the inner cavity and external cavity are L and L_{ext} , respectively. Reflection coefficients of the three mirrors are r_1 , r_2 and r_3 , separately.

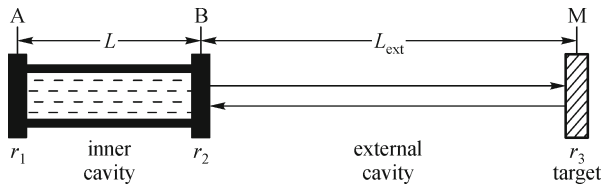


Fig. 1 Schematic diagram of three-mirror cavity self-mixing interferer

From the three-mirror cavity model, the changes of laser’s output gain, frequency and output power are described as below [18]:

$$g_{\text{th}} = g_0 - \frac{\xi}{L} \cos(2\pi f \tau_{\text{ext}}), \quad (1)$$

$$f = f_0 - \frac{C}{2\pi \tau_{\text{ext}}} \sin(2\pi f \tau_{\text{ext}} + \arctan \alpha), \quad (2)$$

$$p = p_0 [1 + m \cos(2\pi f \tau_{\text{ext}})], \quad (3)$$

where, g_0 is initial gain, g_{th} is threshold gain, $f = f_0 + \Delta f$,

f_0 is laser’s initial frequency, Δf is the change of frequency, $\tau = \frac{2L}{c}$ is optical round-trip time in inner cavity, $\tau_{\text{ext}} = \frac{2L_{\text{ext}}}{c}$ is optical round-trip time in external cavity, C is the parameter denote feedback level, α is the laser’s linewidth enhancement factor.

In Eq. (1), the laser’s threshold gain g_{th} is modulated by feedback light. Equation (2) determines the laser’s oscillation frequency. When the length of external cavity is continuously changed, the laser’s oscillation frequency will be altered periodically. In Eq. (3), the laser’s output power is modulated periodically by feedback light. And the changing of phase is determined by frequency property expressed by Eq. (2).

In this model, parameters C and α are very important for laser self-mixing interferer. The parameter C depends notably on the reflection coefficient of the target and the distance to the laser. When $C \leq 0.1$, the feedback level is very weak, and the laser’s output signal is sine waveform; When $0.1 < C < 1$, the feedback level is weak, the LD remains single mode, laser’s output signal is conventional like saw tooth, and the function of optical frequency and output power to time have single solve; When $1 \leq C < 4.6$, the feedback level is moderate, the laser is no longer single mode, laser’s output is also conventional saw tooth like signal. The signal exhibits hysteresis, and the function of optical frequency and output power to time have more than one solves; When $C \geq 4.6$, the feedback level is strong, the signal exhibits seriously hysteresis and the laser are in unstable situation.

The parameter α determines the inclining direction and degree of output signal waveform [11]. When α is very big, $\arctan(\alpha) \approx \pi/2$. And when α increases to a certain degree, $\phi_0(t) = \arctan(\alpha)$ does not change any more. When the laser self-mixing interferer is designed, the parameters C and α should be chose properly.

Figure 2 shows the MEMS structure, which consists of a mass suspended in the horizontal plane by four springs, it is the basic block of many micromechanical devices, including accelerometers, gyroscopes, and other micro-resonators. To actuate the device, and/or detect its vibration amplitude, some combs are built along the sides of the moving mass. For gyroscopes and microresonators, the mass is forced to vibrate along the driving axis (y -axis in Fig. 2) by electrostatic force, and this force is generated by applying a periodic voltage $V_0 + v_0 \sin(2\pi f_0 t)$ to combs. For design optimization, it is often required to monitor the resonance frequency and the quality factor of the mechanical system as functions of the applied sinusoidal and dc voltages v_0 and V_0 , as well as external parameters, such as pressure. The detailed measurement process is introduced as follows.

By Eqs. (2) and (3), the laser’s output power and frequency are modulated. When a small fraction of light emitted by LD is backscattered or reflected by the target,

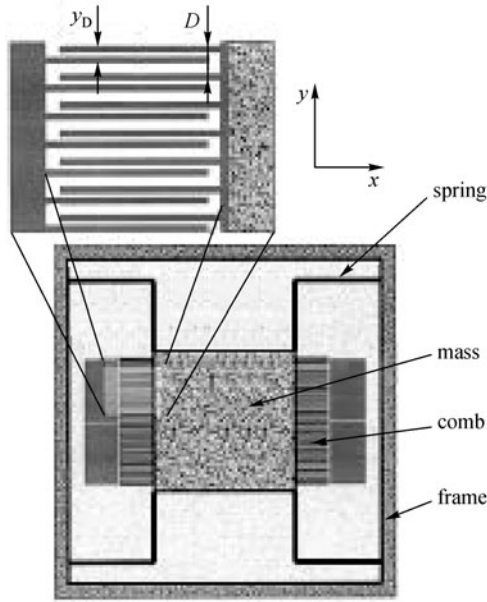


Fig. 2 Schematic diagram of MEMS structure

and re-enter in the laser active cavity. The output power expression Eq. (3) in the term of photoelectric detector (PD) current expressions is expressed as follows.

$$I = I_o + I_{max} \cos(2\pi f \tau_{ext}). \quad (4)$$

In the weak feedback, laser's output frequency is virtually equal to the unperturbed one, $f \approx f_o$. When the target displacement along the direction of the laser beam is $s(t)$, and the target distance at rest is s_o , the output of PD's current is expressed as

$$I = I_o + I_{max} \cos \left[\frac{4\pi}{\lambda} (s(t) + s_o) \right], \quad (5)$$

where λ is laser wavelength.

Through a certain signal processing, the target's displacement can be extracted, for example, in Fig. 3, fringe counting method is used, just by detecting the zero-crossings of the interferometric signal $I_t - I_o$. Namely, if the number of fringes within a half period of the forcing waveform is M (M is four in Fig. 3), the peak-to-peak amplitude of the vibration of the target is

$$s(t) = M \frac{\lambda}{2 \cos \theta}, \quad (6)$$

where θ is the angle between laser beam axis and target vibration direction.

The resonance curve of the mechanical system can therefore be obtained by measuring the displacement amplitude for different frequency of the driving signal, just as Fig. 4. And then the quality factor Q is obtained by $Q = \frac{f_r}{\Delta f}$, f_r is the resonance frequency of the mechanical

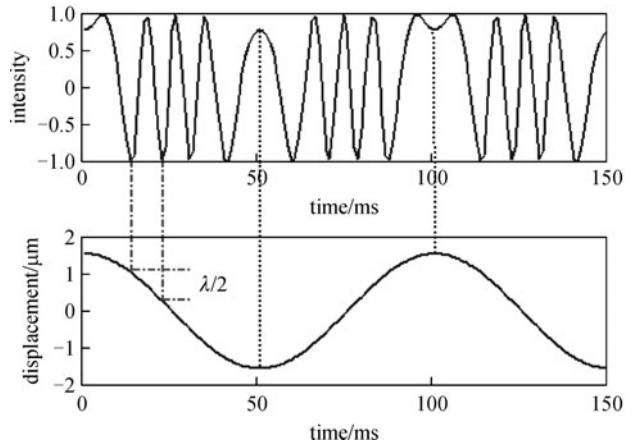


Fig. 3 Signal waveform when the target moves in the way of sine wave

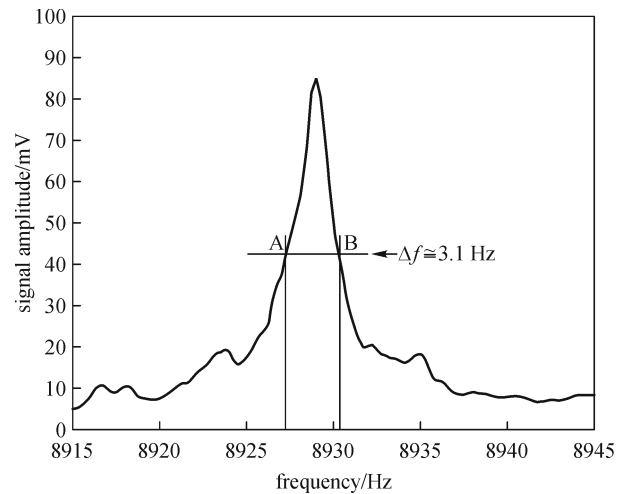


Fig. 4 Schematic diagram of MEMS components resonance curve

system, $\Delta f = f_B - f_A$ is the bandwidth of the resonance, and f_B, f_A is the half power point, where the vibration amplitude is $\frac{1}{\sqrt{2}}$ of the max amplitude.

2.2 Dynamic measurement system of laser self-mixing interferer

Figure 5 shows the dynamic testing system of laser self-mixing interferer. The light emitted by semiconductor laser diode illuminates to MEMS devices by grin lens, and then reflects or back-scatters into laser cavity by MEMS device surface. The laser's output power and frequency are modulated. So the output light has object's movement information. And the movement information, such as vibration amplitude, resonant frequency, quality factor, hysteresis effect, and so on, can be extracted by signal

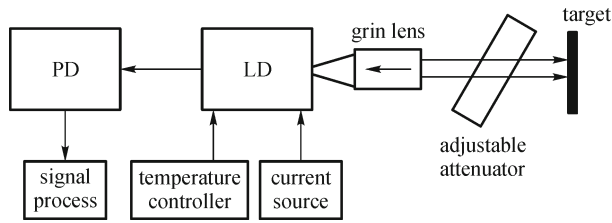


Fig. 5 Principle diagram of dynamic measurement system of laser self-mixing interferer

processing. An adjustable attenuator is used to make the light feedback level optimal. From Fig. 5, it is also found that this dynamic testing system does not need a lot of reflectors, lens, but single light line. So the system is simple, and the light line is easy to be adjusted. The PD, alignment lens and laser can be packaged together, and the laser self-mixing dynamic testing system can become simpler.

The laser diode with advantages of simple structure, high efficiency, ultra-small size, can be modulated with high frequency by drive current [11]. In this system, a semiconductor laser is generally chosen. But semiconductor laser is very sensitive to temperature changes, it is necessary to keep temperature precision [19]. With the development of new structure and technology, this problem can be solved using vertical cavity surface emission laser (VCSEL). VCSEL has good temperature property, and it does not need to undertake precision temperature control. Thus power consumption in the system can be significantly reduced and it is endowed with lower cost [20]. So the laser self-mixing dynamic testing system can be further miniaturization and practical.

Signal processing is the most important for this system. Now there are several kinds of signal processing method, and each has its advantages and disadvantages. For example, fringe counting methods has advantages of big measurement range, but the measurement accuracy is one-half wavelength [21,22]; phase extraction method has high measurement accuracy, but its measuring range is one wavelength [23,24]. The object's different information can be obtained by these different methods of signal processing from laser self-mixing test system including some static information, such as surface morphology.

Figure 5 only shows principle diagram of the testing system. There is a long way to go for practical applications of the laser self-mixing dynamic testing system. Many engineering details have not been taken into consideration in this paper, For example, MEMS devices will be fabricated smaller and smaller, the problems of reducing beam spot diameter and alignment of optical line need to be solved. Moreover, the laser self-mixing is just single point test in this study, how to obtain the full field measurement by scanning technology need to be studied. Therefore, great efforts need to be made for successful applications of laser self-mixing dynamic testing system.

3 Results and discussion

To validate the effectiveness of this method for measuring the movement of MEMS components, piezoelectric machine (PZT) is adopted to simulate different forms of micro movement of MEMS components, and the corresponding self-mixing phenomenon is obtained. Test devices: laser with output power of 5 mW and wavelength of 1550 nm, PZT is WTYD101010, LeCroy oscilloscope is 104XS (1 G bandwidth, 5 G sampling rate), Agilent signal generator is 33250 A. Experimental light is shown in Fig. 6. The laser is fixed in adjustable platform, which has five degrees of adjustable freedom. PZT is fixed on displacement platform, which can used to adjust the position. The whole testing system is located in floating optical platform

Signal generator's output signal (amplitude of $10V_{pp}$, frequency of 6 Hz) with different forms is directly added to PZT. In Fig. 7, the upper waveform is the driving signal,

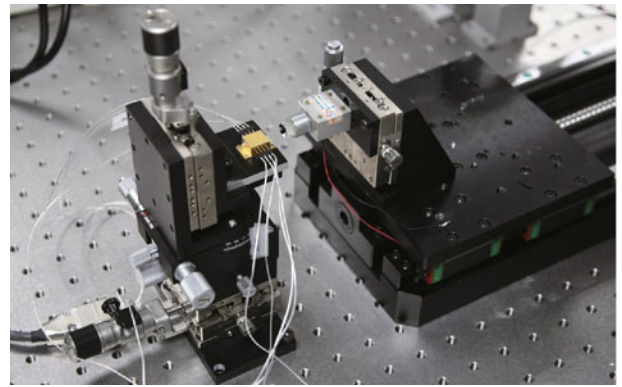
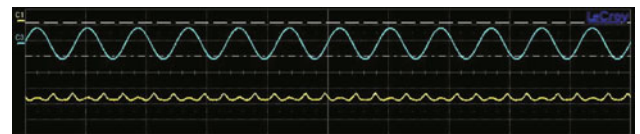
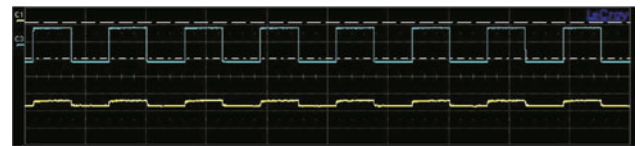


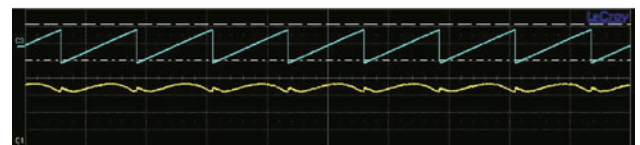
Fig. 6 Light route of self-mixing interferer



(a)



(b)



(c)

Fig. 7 Self-mixing interference with different movement forms of PZT. (a) Sine wave movement; (b) square movement; (c) saw tooth movement

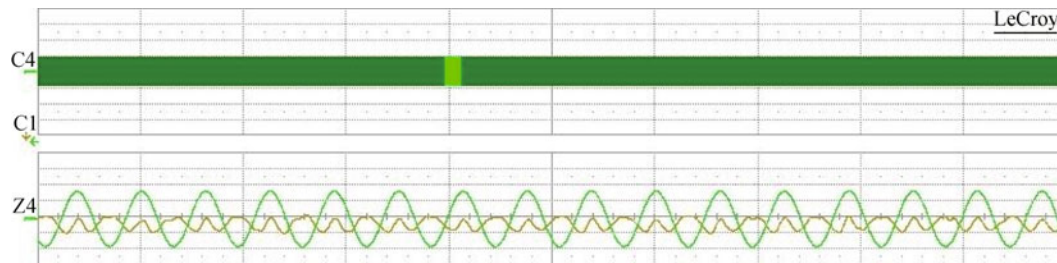


Fig. 8 Self-mixing interference with high frequency vibration of PZT

the lower waveform is the output signal, and the self-mixing phenomenon is very obvious.

Under $10V_{pp}$ driving signal, PZT has a displacement of $1\ \mu\text{m}$, and the output signal can appear a complete interference fringe. The testing results are in accord with those of the theoretical analysis. From Fig. 7, it can be seen that the laser can sensitively reflect object's different forms of movement. Through an appropriate signal processing method, the object's movement information can be extracted. The laser self-mixing interference can also response to high frequency (see Fig. 8), the self-mixing high frequency response is shown that the upper waveforms are driving signal and interference output signal under the sine driving signal with frequency of 2 kHz, and the lower one are its amplified waveforms.

Though this paper just uses PZT to simulate MEMS component's movement, the experiments results show that the laser self-mixing is sensitive to object's different forms of movement. By appropriate signal processing, the movement information of objects can be obtained, so it proved that this method is effective for measuring the movement parameters of MEMS components.

4 Conclusions

In this paper, laser self-mixing measurement was introduced into MEMS dynamic tests. And the measuring principle, test systems and experiments were presented. The experimental results show that laser self-mixing is sensitive to object's different forms of movement by the corresponding signal processing. The movement information of objects can be obtained, such as micro-gyroscope vibration amplitude, resonant frequency and quality factor. It is suggested that the laser self-mixing interferer for MEMS dynamic testing with simple structure, easy alignment, and low cost has huge prospects of applications.

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