FIBER-OPTIC DISPLACEMENT SENSOR BASED ON FABRY-PÉROT INTERFEROMETER

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Abstract: This paper describes a simple and inexpensive fiber-optic sensor for dynamic displacement measurement with sub-nanometer resolution. The principle is based on creating a resonator cavity between measured surface and a single-mode fiber, working as a Fabry-Pérot interferometer. The fundamental principles like diffraction, spatial filtration or the role of reflectivity are analyzed theoretically and their effect on the sensitivity is explained. The sensor is then tested experimentally with an uncoated fiber tip and a gold mirror. Based on the spectral analysis, the effect of working distance on interference visibility is explained.

Keywords: Fiber-optic sensors, Fabry-Pérot interferometer, interferometric measurement, vibration sensing, acoustic emission.

1 INTRODUCTION

Accurate sensing of small distance or displacement is important for various applications, e.g. material surface scanning. For this purpose, methods like atomic force microscopy (AFM) or electron microscopy has been developed [1]. However, this method normally enables only static measurement, where the displacement is not changing over time. Many applications, like vibration analysis of MEMS structures or acoustic emission measurement, require sensing of vibrations in particular point and obtaining a corresponding time-dependent signal within wide frequency range. To satisfy this condition together with sub-nanometer accuracy, the optical interferometry is the best and the most common method [2, 3].

Nevertheless, the optical interferometers are usually complex and large devices, usually requiring stable reference (Michelson interf.) or frequency modulation (heterodyne interf.), and their price can be thus very high. This can be overcome with using optical fibers. For mentioned purpose, various intrinsic or extrinsic fiber-optic interferometers were proposed [4]. However, the highest accuracy combined with relative simplicity was achieved with structure based on extrinsic cavity resonator working as a Fabry-Pérot interferometer, where a noise density of $\mathrm{fm}/\sqrt{\mathrm{Hz}}$ was reached [3].

The sensing probe consists of an ordinary single-mode (SM) fiber, whose tip is placed near the sensed surface (Fig. 1). Like in any interferometer, the output is given as an interference of two waves, one of which is influenced by the measured physical quantity. In this case, the interference occurs between the light reflected from the fiber edge and the light propagating to the air cavity and coupling back to the fiber. In comparison to the free-space interferometers, this setup has many advantages. Not only the sensing probe is very subtle and the phase of the reference beam is fixed well, but especially the fact that the sensing beam can pass through the cavity many times means that it can operate as a high-finesse resonator [5]. As a result, the sensitivity can be increased many times in comparison to the two-beam interferometers.

The best known utilization of the fiber-optic sensor based on Fabry-Pérot interferometer is the atomic force microscopy mentioned before, where the vibrations of the oscillating cantilever are sensed [1, 3]. In this case, the frequency of the vibrations is measured, whereas the amplitude is maintained in its maximum by adjusting the cavity length. However, for dynamic surface vibrations sensing, it is important to transfer the surface displacement to the phase shift directly and also measure the amplitude. In this paper, the basic principles of the fiber-optic small displacement sensor are described theoretically and the first experimental data are provided.

2 THEORY

The main sensing part consists of a cleaved SM fiber tip, which is placed close to the sensed reflective surface, so there exists a plane-parallel air-filled cavity working as a resonator, as show in fig. 1. The principle is similar to the Fabry-Pérot interferometer. Due to the Fresnel reflection on the boundary of the fiber and the cavity, one part of the incident light is reflected back, whereas the other part is propagating to the cavity. This light beam is then reflected back from the sensed surface and partially coupled back to the fiber with the phase shift equal to

$$\Delta\phi = \frac{4\pi n d}{\lambda}, \tag{1}$$

where n is the refractive index (in air is close to 1), λ is used wavelength and d is the width of the cavity. After the interference of both beams the output intensity is given as

$$I_{\text{out}} = I_0 \left[1 + V \cdot \cos(\Delta\phi)\right], \tag{2}$$

where V is a visibility of the interference and I_0 is a mean value, because the powers of the beams are usually not equal. Most of the light propagating through the cavity is not coupled to the fiber core, but instead, is reflected back by another Fresnel reflection. The portion of reflected power can be increased by various metal coatings (the reflectivity of silica glass is normally only about 4 %). The beam can thus bounce between the reflective sensed surface and the partially reflective fiber facet many times before it is coupled back to the fiber. In this case, a more complex effect of a multiple-beam inteference occurs in the sensing fiber. Neglecting any losses, the output intensity is now given as

$$I_{\text{out}} = I_{\text{in}} \frac{F \sin^2 \frac{\Delta\phi}{2}}{1 + F \sin^2 \frac{\Delta\phi}{2}}, \tag{3}$$

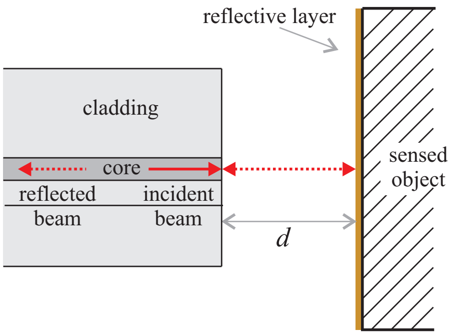

Figure 1: Schematic of the sensing part of the fiber-optic displacement sensor.

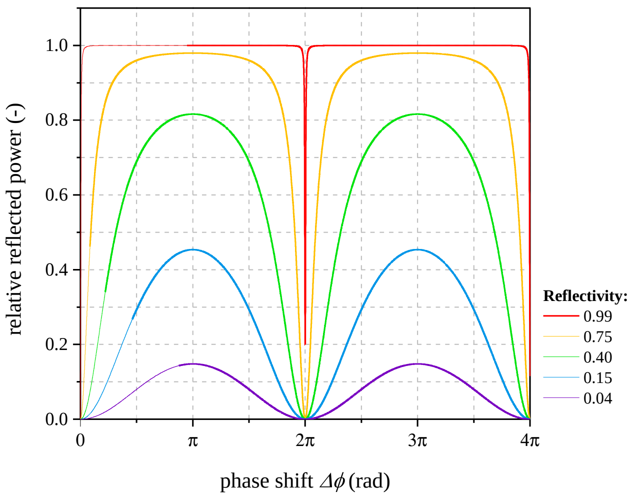

Figure 2: Normalized interference characteristics of the sensor when the reflectivity r is changed.

where I_{in} is the input intensity and F denotes the finesse of the resonator, which basically determines the sharpness of the resonance, and can be defined as $F = 4r/(1-r)^2$, assuming the both reflectivities are equal to r. It can be shown that for small reflectivity, and thus small finesse, the output response may be simplified to the form given by eq. 2. The calculated dependence of the output intensity on the phase shift by different values of the reflectivity is displayed in fig. 2. It is obvious that the slope of the portions which are approximately linear is rapidly increasing if the reflectivity is high, so the sensitivity to displacement changes Δd is large.

However, the high reflectivity is not the only requirement for reaching the high sensitivity. To achieve high visibility, the reflectivity of the sensed surface must be balanced with the effective reflectivity of the fiber facet. This is related to the another issue, which is a spatial filtration of the SM fiber. Virtually, the beam escaping from the fiber tip is always diverging. The divergency angle is given especially by the fiber diameter, its numerical aperture and used wavelength. As consequence, only a small portion of the reflected beam can be coupled back to the core of the fiber. Most of it is either coupled to cladding or reflected back, so it continues in diverging until it is diffracted outside the resonator. Further, the cladding modes with different phase shift can interfere with the core modes which also has a negative influence on the total sensitivity.

To summarize, it is especially the mentioned effects of diffraction and the spatial filtration which make this principle more complex than the ideal Fabry-Pérot interferometer. The amount of these unwanted effects can be eliminated by making the working distance d small enough, so a sufficient portion of the light can be coupled back even after multiple reflections inside the cavity. Also, it is very crucial to align both surfaces precisely, otherwise only one reflection can occur. The total sensitivity is thus dependent not only on the reflectivities and their mutual balance, but also on the working distance, alignment and SM fiber parameters.

3 EXPERIMENTAL SETUP

As mentioned before, the highest sensitivity to the displacement changes Δd can be reached when the static phase diffence $\Delta\phi$ for the working distance d corresponds to the steepest part of the curves in fig. 2. Moreover, within some small region around these points, the response characteristics can be considered to be approximately linear. It is thus convenient to maintain the distance d within this region, so the output intensity directly tracks the actual vibrations $\Delta d(t)$. Since the optimal working distance is in order of units or tens of micrometers, the best way to adjust the working distance is to use a piezoelectric-driven actuator. The similar principle is also used in AFM, where the small vibrations of the cantilever are sensed. Here the source is usually a laser diode coupled to a SM fiber. The output is then detected by a photodiode and after processing it is fed back to the actuator maintaining the distance d in the optimal region.

The test setup used for the experimental implementation of described fiber-optic sensor is schematically illustrated in fig. 3. In this case, an ordinary telecom SM fiber SMF-28 is used, with a precise cleave at the end, without any additional coating. Therefore, the portion of the light reflected on the fiber-air boundary is relatively low. The fiber tip is attached to a glass base, which is fixed to a 3-axes precise positioning stage. As a sensed material, a mirror with a gold coating is utilized to achieve high reflectivity (> 0.95) for used wavelength range. The mirror is attached to a differential kinematic mount, which allows very fine adjustment of the incident angle. To investigate the resonance cavity characteristics in a wider range, a broadband superluminiscent diode (SLD) source Thorlabs S5FC1005S (wavelength rage 1290-1650 nm) was used. To separate the input and the output beam, an optical circulator was used. The output power was then measured by the optical spectrum analyzer (OSA) Advantest Q8384 (resolution 10 pm) controlled by the LabVIEW program for fast data acquisition. As a consequence, a response of the cavity for multiple wavelengths is obtained in the same time. It can be shown that this is equivalent to the measuring of the response for single wavelength when the stage is linearly moved towards or from the mirror plane. However, if the sensing fiber is moved, the effective reflectivity is also changing slightly so the result could be non-uniform. Therefore, the wavelength sweep is more robust and effective method of cavity response characterization.

4 TEST MEASUREMENT

The output spectral response of the fiber-optic interferometer was measured for different values of the distance d ranging from 170 µm to about 2.6 mm. The relative amount of reflected power for particular wavelength is plotted in fig. 4. For each distance, the tilt of the mirror was adjusted to achieve the maximum of the power coupled back to the fiber. Within the displayed region, all the spectral responses can be considered as periodical functions of wavelength. The period is given by the free spectral range (FSR), which can be expressed as

$$FSR = \frac{\lambda^2}{2d}, \tag{4}$$

so it is also wavelength dependent. It can be seen that the total reflected power is increased when the fiber is closer to the mirror. It can be easily explained by the fact that the beam inside the cavity is diverging, so the total re-coupled power is indirectly proportional to the distance d.

Further property which can be noticed from the fig. 4 is the dependence of the visibility $V(d)$, or the contrast of the interference. The visibility, and thus high dynamic range of distance sensing, is maximal when the powers of interfering beams are equal. Since the portion of the light reflected by Fresnel reflection on the boundary between the fiber and air cavity is low, it can be easily exceeded by the power reflected from the mirror and coupled back to the fiber for smaller distances d. This is the case of the curve corresponding to the distance $d = 170$ µm. On the other hand, when the distance is too large, the power re-coupled is very low and also the visibility is decreasing. The optimal distance for the bare SM fiber was approximately 364 µm, when the output intensity can drop down by more than 21 dB between constructive and destructive interference.

Assuming the spectral resolution to be $\Delta\lambda_{\text{min}}$, the resolution of the distance detection is

$$\Delta d_{\text{min}} = \frac{\lambda \cdot \Delta\lambda_{\text{min}}}{2 \cdot FSR}. \tag{5}$$

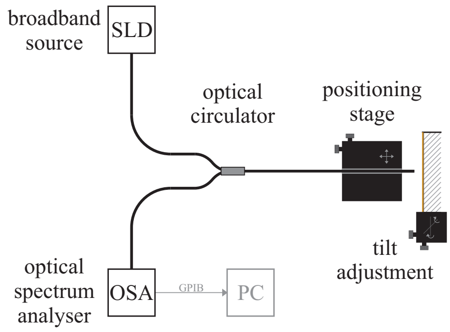

Figure 3: Schematic of the experimental setup.

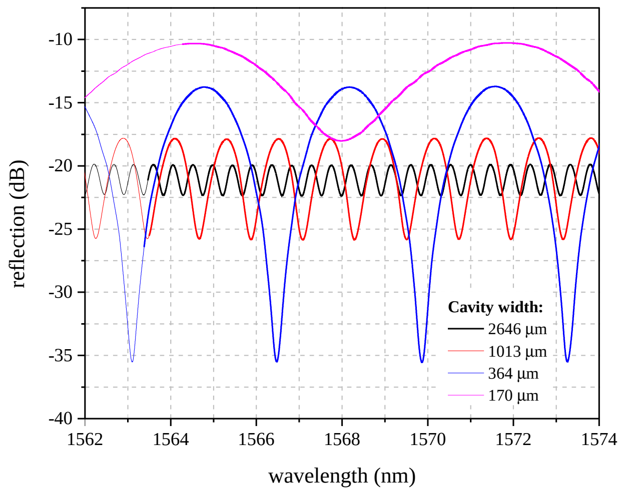

Figure 4: Relative spectral reflectivity of the fiber-optic sensor with different cavity width d.

With the used OSA, the resolution achieved for $d = 170$ µm is therefore about 1 nm. However, the detection from the spectrum can only be used for static distance sensing, whereas for vibrations measurement an intensity by single wavelength is sensed, as described before. Therefore, the sensitivity is determined by the visibility and the slope of the resonance dip. In this experimnetal setup, the interference characteristics corresponded to the curve in fig. 2 with $r = 0.04$. From the fig. 2 it is obvious that the sensitivity could be yet increased by many times when the fiber edge would be coated.

5 CONCLUSION

The fiber-optic sensor for accurate displacement measurement was studied theoretically as well as tested by the experiment. In comparison to the common free-space interferometers, the described principle has advantage of reduced size, low price due to its simplicity, and also avails from the robustness of fiber-optic sensors. Further, the sensitivity can be highly increased by the resonator nature of the cavity, similar to the Fabry-Pérot interferometer. However, it was discussed and showed by the experiment that the behavior of the extrinsic fiber cavity is strongly influenced by the reflectivity of both surfaces, their matching, alignment, but also the effects of dispersion and spatial filtration of the SM fiber. It was also shown that for a given fiber reflectivity, there exists some optimal sensing distance, where the visibility reaches the maximum. Further, the total sensitivity could be increased by adding a fiber coating.

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