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Investigation of evanescent scattering for low-distortion submicron vibration sensing using ferromagnetic cantilevers

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Abstract: In this study, we investigate the dynamic performance of a previously reported evanescent-scattering platform for submicron vibration sensing with low distortions. The platform consists of self-assembled ferromagnetic cantilevers located above a liquid-cladded optical waveguide. Theoretical analyses show enhancement of sensitivity and dynamic sensing range by reducing the waveguide core-cladding index difference. Moreover, a careful tradeoff between sensitivity and linearity is required, which is determined by the bias position of the cantilever tip. Experimental results confirm that our platform can offer low total-harmonic-distortions (THD) of < 3.00% with a submicron displacement of 0.40 µm over the frequency range from 80 Hz to 750 Hz. The measured THD value is very close to our theoretical prediction. Thus, our platform can be employed in submicron vibration sensing with high-precision requirements.

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1. Introduction

Optical vibration sensor in submicron range has been employed in active vibration isolation structural health monitoring, and online vibration feedback [1,2]. The sensing principles are classified mainly as interferometric and non-interferometric methods. Interferometric methods, such as laser doppler vibrometers (LDVs), provide nanoscale resolution but demand stringent optical alignment, which leaves large footprints and entails high building costs [3–6]. Alternatively, non-interferometric methods, such as fiber micro-bending and optical coupling, leave small footprints but are either insufficiently sensitive to micrometer-scale vibrations or weak in sensing reliability [7–13]. Fiber Bragg grating (FBG) vibration sensors, which are commercially available, offer reliable vibration feedback and high sensitivity [14,15]. However, it desires a coherent light source and highly relies on the wavelength interrogations, leading to low interrogation speed and high cost as picometer-resolution systems are indispensable [16–18]. A recent evanescent-coupling platform that uses microcantilevers offers sensitivity comparable to LDVs and leaves a smaller footprint [19]. This platform operates at intensity interrogation mode and does not require the coherent light source. However, it has two main drawbacks. First, building costs remain high owing to complex cantilever micromachining, and second, evanescent coupling is highly wavelength dependent. However, these drawbacks can be circumvented by our recently proposed evanescent-scattering system [20]. First, evanescent scattering is generally less wavelength dependent compared with evanescent coupling. Second, the evanescent scattering in our platform is induced by self-assembled ferromagnetic cantilevers, which are easy to form and thus affordable. However, achieving a linear sensing response under a nonlinear evanescent field is challenging. Hence, we investigate how a linear response can be achieved over a desired dynamic range through optimization of sensor designs. These include proper design of optical waveguide and careful positioning of cantilevers into the evanescent field.

Theoretical and experimental investigations are performed and compared in this work. A simplified model that considers a single ferromagnetic particle is used to simulate transmission
loss at different waveguide-cladding indices. Only transverse magnetic (TM) polarization is considered for high scattering efficiency [20]. The theoretical investigations mainly address sensitivity enhancement, increase of dynamic sensing range, and linear response based on liquid claddings as well as the bias position of the cantilever tip. Experimental results confirm that our platform can offer low total-harmonic-distortions of < 3.00% at a submicron displacement of 0.40 µm. The low THD generates considerable advantages for our platform, such as excellent linearity and high precision in submicron vibration sensing.

2. Sensing principle and simulation analysis

Figure 1(a) depicts the schematic diagram of our proposed vibration-sensing design. The nonbrittle ferromagnetic cantilevers are formed by stimulating a mass of micron-sized iron particles under external magnetization [20]. Figure 1(b) shows that these particles aggregate, self-assemble, and form multiple cantilevers held by a magnetized blade. The formation process is easy and low cost. We employ a Piezoelectric transducer (PZT) as the vibration generator, which imposes vibrations onto the blade to create cantilever vibrations. We carefully position the cantilevers on top of a liquid-cladded channel waveguide before the operation to facilitate evanescent scattering. Evanescent waves will scatter when the cantilever tip particles show proximity to the waveguide surface, thereby leading to transmission loss with respect to vibrations. The shape of the blade can be designed for miniaturization or package uses.

![Fig. 1.](image)

**Fig. 1.** (a) Schematic diagram of the platform for illustrating the sensing principle; (b) microscopic view of self-assembled ferromagnetic cantilevers.

Scattering efficiency is mainly determined by the gap distance \(d\) and the evanescent penetration depth \(d_p\). As shown in Fig. 2(a), \(d\) is defined as the distance between the cantilever tip and the top surface of the optical waveguide. Meanwhile \(d_p\) is commonly described as the evanescent penetration depth [21], expressed as \(d_p = \lambda_0/[2\pi(n_{eff}^2 - n_L^2)]^{1/2}\), where \(n_{eff}\) and \(n_L\) refer to the waveguide mode effective index and upper cladding index. Scattering efficiency, which is evaluated in transmission, is simulated based on a simplified model, in which a single iron particle (diameter \(D\)) is considered. We assume that the particle locates on the central plane on top of the waveguide (core width \(w\), height \(t\)) with gap distance \(d\). Perfectly matched layer (PML) condition is used on all surroundings. To keep the fabrication in consistency, we chose the same geometry dimension and materials system as mentioned in our previous report. Their parameters were depicted in Fig. 2(a) caption. The sensor performance was then tuned by varying the upper cladding index \(n_L\). We employed Finite-difference-time-domain (FDTD) simulation to investigate three different cases when \(n_L = 1.470, 1.515, \) and 1.525 as shown in Fig. 2(b). It should be noted that the optimal sensitivity for our vibration sensor can be achieved when liquid cladding index is close but not greater than 1.528 according to the FEM simulation using COMSOL Multiphysics. However, due to unavailable liquid cladding in our lab for experimental verification, we chose the
closest index value, \(n_L = 1.525\) for our study. All the curves illustrate nonlinear transmission loss against \(d\) at a range from \(0 \mu m\) to \(\sim 9.00 \mu m\). Moreover, the blue curve shows the largest dynamic sensing range (\(\sim 9.00 \mu m\)) compared with the others (\(\sim 1.50 \mu m\) for the black curve, and \(\sim 3.00 \mu m\) for the red curve). This finding is due to a low core-cladding index difference, which expands the occupation of the evanescent field in the liquid cladding.

Fig. 2. (a) Simulation model, \(D = 7.00 \mu m, t = 1.80 \mu m, w = 5.00 \mu m, \) core index \(n_C = 1.541, \) lower cladding index \(n_{\text{Clad}} = 1.514; \) (b) simulated transmission loss by a single iron particle for \(n_L = 1.470, 1.515, \) and 1.525; simulated sensitivity comparison in (c) and linearity comparison in (d); and (e) simulated frequency spectrum for position B at a vibration frequency of 250 Hz.

Apart from the dynamic range, we are also concerned with the sensitivity and linearity of the sensing response for a desirable sensing performance. In Fig. 2(c), sensitivity, defined as \(\Delta T/\Delta d\), is compared at different \(d\) for \(n_L = 1.470\) and 1.525. The maximum value of sensitivity for \(n_L = 1.525\) is \(\sim 0.3 \mu m^{-1}\), and the sensitivity is constantly larger than that of \(n_L = 1.470\) over a long range to \(\sim 6.00 \mu m\) before returning to zero. The finding is due to the enhancement of evanescent penetration into the liquid cladding. Thus, choosing a large \(n_L\) is desirable for high sensitivity uses. We choose \(n_L = 1.525\) in the experiment to avoid a waveguide fundamental mode cutoff. In addition to \(n_L\), the initial particle position \(d\) also affects sensitivity. In the case of \(n_L = 1.525\), we label three positions, namely, A, B, and C, to mimic the bias position of the tip particles in the evanescent field. Position A (\(d = 1.00 \mu m\)) offers the highest sensitivity among positions A, B (\(d = 2.50 \mu m\)), and C (\(d = 5.00 \mu m\)). The adjusted coefficient of determination, i.e. \(R^2\), which varies between 0 and 1, is used to evaluate signal linearity at different bias positions. Figure 2(d) depicts the comparison of \(R^2\) values against the dynamic displacement \(\Delta d\), which varies from 0.10 \(\mu m\) to 1.50 \(\mu m\) for positions A, B, and C. For a given value of \(\Delta d, R^2\) at positions A, B, and C are constantly in ascending order. Given that a large \(R^2\) value implies high linearity, positions A, B, and C will be in ascending order in the dynamic range with the same linearity. Thus, a tradeoff exists between sensitivity and dynamic sensing range once \(R^2\) is predefined. Moreover, these two factors need to optimize accordingly with respect to practical sensing applications. In Fig. 2(e), we simulate a case for position B when \(\Delta d = 0.40 \mu m\) at 250 Hz. The calculated power difference between the fundamental and 1\(^{st}\) harmonic order is 30 dB, corresponding to the
A $R^2$ value of 0.9990. For a simple evaluation of signal linearity in the frequency spectrum, we correlate $R^2$ with THD, which is defined as $\text{THD} = (V_2^2 + V_3^2 + V_4^2 + V_5^2)^{1/2}/V_1$, where $V_i$ ($i = 1, 2, \ldots$) denotes the root-mean-square voltage of the $i_{th}$ harmonic, and $i = 1$ is the fundamental frequency. For reference, the calculated THD value for the case of Fig. 2(e) is $\sim 3.17\%$.

We can easily obtain THD by analyzing frequency spectra of transduced vibration signals. By correlating $R^2$ with THD, we can get the maximum $\Delta d$ to obtain a desired linearity with respect to the frequency spectrum by referring to Fig. 2(d). For $R^2 = 0.9990$, the maximum $\Delta d$ is intersected in Fig. 2(d) as $\sim 0.36 \mu m$, $\sim 0.40 \mu m$, and $\sim 0.49 \mu m$ for positions A, B, and C, respectively. This result indicates that our vibration-sensing platform can have a quasilinear sensing range of $\sim 0.40 \mu m$. This value can be extended by further optimizing waveguide designs and material choices. A bias position located between A and C is preferable in our case for submicron vibration-sensing applications by considering combined sensitivity, linearity, and dynamic sensing range. This position should be carefully located to obtain maximum symmetric sensing responses, which will be discussed further in Section 4.1.

3. Sensing platform preparation and characterization

The sensing platform consists of two main components, namely, ferromagnetic cantilevers and a channel waveguide. Both components were prepared based on the process described in [20]. A careful waveguide leveling process was performed prior to dripping the index-matching liquid on the waveguide surface. The refractive indices of the epoxy cladding $n_{\text{clad}}$ and the benzocyclobutene (BCB) core $n_c$ at 1.550 $\mu m$ were 1.514 and 1.541, respectively, and the thickness of the epoxy film was 4.85 $\mu m$. The BCB core height $t$ and width $w$ were 1.80 $\mu m$ and 5.00 $\mu m$, respectively. These parameters ensured that the channel waveguide was a single mode. The sensing length was adjusted to $\sim 2 \text{mm}$ for a reasonable sensitivity, which can be varied with respect to designs.

Figure 3 shows the experimental setup for characterizing the sensing platform. The setup was placed on a vibration-isolated optical table to ensure that the main vibration was induced by the PZT. The magnetic blade screwing in PZT was mounted on a high-precision micro-positioner. The initial $d$ was adjusted roughly by the mechanical positioner and precisely by the DC biased voltage applied to the PZT. A 1.550 $\mu m$ distributed feedback (DFB) laser was coupled to the channel waveguide. A linear polarizer was used to select the TM polarization. The PZT (NPX200, 200 $\mu m$) was driven by a signal generator. The electromagnet below the waveguide was used to provide an external magnetic field to form the cantilevers. Optical signal and the PZT driving signal were displayed in the oscilloscope. We applied a free-space external Fabry–Perot interferometer (EFPI) to calibrate PZT displacement. As shown in Fig. 3 inset, a full mirror (reflectivity, $R \sim 1$) was adhered onto the blade, and a half mirror (R $\sim 0.4$) was fixed parallel to the

Fig. 3. Experimental setup for characterizing the sensing platform.
full mirror, with a cavity gap filled by an index-matching liquid of $n = 1.500$. As the full mirror vibrated, the reflected power produced sinusoidal signal fluctuations with multiple fringes [black line in Fig. 4(a)]. The displacement can be calculated by counting the fringe number $N$ as $d_{PZT} = N\lambda_R/2ncos\theta$ [22–24], where $N$ is the fringe count in the semiperiod of the PZT driving signal [blue lines in Fig. 4(a)], $\lambda_R$ is the light wavelength (633 nm), $n$ is the refractive index of the matching liquid, and $\theta$ is the incident angle ($\sim 2.5^\circ$ in our case).

Fig. 4. (a) Real-time EFPI fringes (black) and PZT driving signal (blue); (b) optical output at different PZT biased voltage; (c) light output for purple line in (b); (d) calculated $R^2$ for (c).

4. Experimental result and discussion

In this section, we experimentally investigated the performance of the vibration-sensing platform in two aspects. First, we experimentally determined an optimal initial location $d_0$ by achieving the maximum symmetrical sensing response. Second, we investigated the frequency response of the platform based on the determined $d_0$ by setting the sensing range in a quasilinear region to ensure that the cantilever displacement $\Delta d_C$ was within 0.40 $\mu$m.

4.1. Determination of an optimal $d_0$ for maximum symmetric response

The blade-held ferromagnetic cantilevers were carefully placed into the evanescent field by a micropositioner. Then, the PZT imposed a 40 Hz sinusoidal vibration with a displacement of $\Delta d_{PZT} \sim 2.53$ $\mu$m to the cantilevers, as shown in Fig. 4(a). We imposed same displacements to seek the symmetric scattering region but gradually lowered the PZT toward the waveguide by tuning the PZT bias voltage. The optical outputs in different colors in Fig. 4(b) express the cantilevers vibration at different signal symmetries. The symmetry variations revealed that the cantilevers were located at different initial positions in the evanescent field, that is, highly asymmetrical (black), asymmetrical (red), symmetric (purple), and saturated (green) regions. The asymmetries were due to large sensitivity asymmetry within the vibration displacement, which is in correspondence with theoretical analysis in Fig. 2(c). This asymmetry can be suppressed by gradually lowering the cantilevers into the evanescent field, as indicated by the purple line. However, if the cantilever tip is too close to the surface, it would snap touch the waveguide while vibrating. In conventional micromachined cantilevers, this snapping touch could generate high risks for damages for cantilevers. However, this incident rarely occurred in our cantilevers,
because they realigned and formed new cantilevers owing to flexible ball-joint connections. A simple recalibration process is needed in the event of unexpected snapping touches.

In Figs. 4(c) and 4(d), we investigated the sensitivity and signal linearity of the symmetric purple line. Figure 4(c) compares the optical output against the $d_{\text{PZT}}$, in which the fitting line deformed at a large $d_{\text{PZT}}$. The vibration displacement sensitivity can be roughly calculated to be $\sim 0.34 \, \mu m^{-1}$. Figure 4(d) shows the calculated $R^2$ for the $\Delta d_{\text{PZT}}$, in which linearity dropped as the $\Delta d_{\text{PZT}}$ increased. Both results corresponded well with the simulation results in Figs. 2(c) and 2(d). The corresponding $\Delta d_{\text{PZT}}$ was $\sim 2.10 \, \mu m$ by intersecting $R^2 = 0.9990$ in Fig. 4(d). This indicated a large dynamic sensing range at a high degree of linearity. We can approximately calculate the transmissibility of the cantilevers by referring to $\Delta d_{\text{PZT}} / \Delta d_{\text{C}} \sim 0.19$ at a frequency of 40 Hz. Transmissibility varied at different frequencies owing to mechanical resonance. We positioned the cantilevers similar to the purple line to further investigate the frequency response of the proposed sensing platform at a submicron vibration. Then, we swept the PZT driving frequencies from 80 Hz to 750 Hz at a fixed PZT displacement of $\sim 0.40 \, \mu m$ through the controller and EFPI feedback.

### 4.2. Frequency-sensing response at submicron vibration

We investigated the frequency response of the proposed submicron vibration sensing platform after determining the optimal bias position. Figure 5(a) displays a typical fast Fourier transform (FFT, Tektronix TBS1102B-Edu) spectrum at 270 Hz with temporal response shown in the inset. The horizontal sampling points were set to 1024 and the vertical power reference level was set to $-75$ dB. The spectrum contained peaks of fundamental and multiple harmonics. The fundamental frequency was clearly detectable with a high degree of power extinction with its harmonics, which was greater than 30 dB of the extinction ratio. In addition, the relative error between fundamental and driving frequencies was less than 0.13%, indicating excellent frequency-transducing accuracy.

![Fig. 5. (a) An example of FFT spectrum at 270 Hz and with temporal response inset; (b) measured cantilevers frequency–amplitude response; (c) THD values at discrete frequencies.](image)

The frequency–amplitude response of the cantilevers is depicted in Fig. 5(b), in which we monitored the optical output at discrete frequencies from 80 Hz to 550 Hz. The resonant peak appeared at $\sim 243$ Hz. Given that the PZT vibration displacement had been fixed, resonance will be determined only by the properties of the formed ferromagnetic cantilevers and the index-matching liquid. Theoretically, the frequency–amplitude response can be expressed by the transmissibility of the cantilevers. The cantilever structures can be considered as the damped simple harmonic motion system, and its transmissibility $T_C$, can be described as [25].

$$T_C = \frac{\Delta d_{\text{C}}}{\Delta d_{\text{PZT}}} = \sqrt{1 + \left(\frac{2\zeta \omega}{\omega_0}\right)^2} \frac{1}{\sqrt{(1 - \frac{\omega^2}{\omega_0^2})^2 + (2\zeta \omega)}},$$

(1)
where $\omega$ and $\omega_0$ represent the driving and resonance frequencies, respectively, $\zeta$ refers to the damping coefficient, and $\omega_0$ is determined by the physical properties of formed cantilevers and the index-matching liquid. The physical properties included the cantilevers’ size, mass, modulus, liquid density, liquid viscosity, and so on. The damping coefficient $\zeta$, which determines the quality factor of the curve, is closely related to liquid viscosity and mutual interactions between adjacent cantilevers. Moreover, the modulus of formed ferromagnetic cantilevers can be potentially tuned by enhancing particle-particle interactions. These interactions enhancement can be achieved by applying an external magnetization through a magnetic field [26]. This finding indicated another advantage of the proposed sensing platform, that is, the sensing range can be potentially tuned in real time by regulating an external magnetic field. The verification of tunable characteristics will be performed in future works.

We calculated THD by counting the first four harmonics of FFT spectra, as shown in Fig. 5(c). The maximum THD was less than 3.00% over a frequency range of 80 Hz to 750 Hz, which is very close to our simulation prediction of $< 3.17\%$ by referring to Fig. 2(e). This result indicated negligible distortions and high degrees of linearity in the transduced vibration signals and may be of considerable importance in vibration sensing where high reliability is desirable. Compared with complex micromachined cantilevers, our platform displayed several advantages. Specifically, it is affordable, easy to fabricate, low wavelength dependency of evanescent scattering, and highly sensitive owing to cumulative cantilever arrays. Moreover, it displays a potentially tunable sensing range through magnetic regulation and has low operation risks owing to the nonbrittle property of cantilevers.

It is important to mention that the sensing accuracy is sensitive to the environment temperature. The temperature variation changes the refractive indices of materials, modifies the waveguide design and thus impacting the evanescent power fractions in the liquid cladding. The investigation of temperature crosstalk was performed by measuring the static power fluctuation at different environmental temperatures. Given that our waveguide core and cladings exhibit large thermal-optic coefficients (TOCs) differences, our sensor displays a moderate temperature crosstalk at $\sim 0.06 \text{dB/}^{\circ}\text{C}$ for a range at $\sim 19.5 \pm 5 \^{\circ}\text{C}$. This value can be potentially further reduced through proper choice of waveguide materials which possess similar temperature-optic coefficients.

Table 1 gives comparisons of the vibration sensing performance between the evanescent scattering platform proposed in this investigation and the other configurations cited in this article. The comparison illustrates that the evanescent field sensors (including evanescent scattering)
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coupling and scattering) provide highest vibration displacement sensitivities in micrometer scale when compared to others work. In addition, our evanescent scattering platform employs advantages of simple fabrication, low cost and low wavelength dependency as well. Therefore, the developed evanescent scattering vibration sensor can be a competitive candidate for use in practical submicron vibration sensing applications.

5. Conclusion

We investigated the performance of an evanescent-scattering platform, which we used for low-distortion submicron vibration sensing. Characteristics such as sensitivity, dynamic sensing range, and linearity were theoretically analyzed and further optimized by reducing the core-cladding index difference of the sensing waveguide and biasing the positions of cantilever tips. Experimental results confirm that our platform can offer low total-harmonic-distortions (< 3.00%) with a submicron displacement of 0.40 µm over the frequency range from 80 Hz to 750 Hz, which is very close to our theoretical prediction of < 3.17%. The formed ferromagnetic cantilevers resonated at ∼243 Hz, which can be potentially tuned through external magnetic field regulations. Compared with micromachined microcantilevers, the proposed vibration-sensing platform demonstrated advantages such as low fabrication costs, low wavelength dependency, less operation risks, and a potentially tunable sensing range. Thus, the proposed platform can be employed in potentially low-frequency sensing applications in which high reliability and precision are required.

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Disclosures

The authors declare no conflicts of interest.

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