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Optimal coating thickness for enhancement of optical effects in optical multilayer-based metrologies

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ABSTRACT

We theoretically determine an optimal configuration for a planar optical multilayer that is used to enhance the radiation pressure (RP) and the thermal heating in fiber-based metrology systems such as fiber-top cantilevers. The RP exerting on the metallic layer of the cantilever and the thermal heating due to optical absorption are enhanced. This enhancement can be employed to control the deflection and the vibration amplitude of the cantilever. The thicknesses of the cantilever and the coating layer for maximal RP are shown to be 50–60 nm and 20–40 nm, respectively, when a laser with an optical wavelength $\lambda > 500$ nm is used. The RP amplification due to the cavity effect is most effective at $\lambda \simeq 1200$ nm and reaches a maximum value of 30. The heat absorption of the corresponding films is discussed. These results would be useful for optimizing the configurations of optical multilayer-based devices.

1. Introduction: Optical fiber-based metrologies

Optical fiber-based sensors are of intensive interest for use in performing measurements under critical conditions because of their fabrication simplicity in comparison to other available sensor devices [1–6]. These sensors, with their small heads, cause little interference with test samples and they can help to obtain high-accuracy results. Optical fibers can be combined with high-reflection surfaces to form a Fabry–Perot (FP) interferometer for displacement sensing [7–10] or they can be directly irradiated on the back of a cantilever to provide optical cavities for use in optomechanical laser cooling [11,12] (see Fig. 1(a)). Using this type of mechanism, Kim et al. [13] developed a cantilever-based optical interfacial force microscope to measure molecular interactions in liquids and obtained force resolution of less than 150 pN. Choi et al. [14] fabricated an FP sensor by cascading a photonic crystal fiber in combination with optical fibers for thermal sensing and temperatures of up to 1000 °C could be measured using this optical cavity.

Recently, Iannuzzi et al. [16,17] fabricated a fiber-top cantilever (FTC) by carving the end of an optical fiber [see Fig. 1(b)] and provided measurement abilities in both air and liquids that match those of commercial atomic force microscopes [18–20]. A similar system was used by Li et al. [21] in which an FTC was implemented for temperature sensing at temperatures of more than 500°C. In these systems, the cantilever's frequency shift and deflection are detected by observation of the interference between the light that is reflected at the cantilever and the light that is reflected at the coating layer with thickness t_C at the fiber end, as per common optical fiber interferometers [9,22,23].

However, the roles of the coating thickness t_C and the cantilever thickness t have not been studied to date and the experimental basis for their fabrication is still open to question. The dimensions of the cantilever, for example, are determined based on its mechanical properties, which are planned to provide optimized readout data. Simultaneously, the use of a structure that can optimize the optical control of the cantilever has not been taken into account. In addition, the coating thickness shows an important role in the enhancement of the optical fields. Therefore, a full-scale study of the resonance effects, which are dependent on the coating, is necessary for accurate fabrication of optical cavities and FTCs.

Multiple parallel thin films can be used as filters for optical devices with wavelength-dependent transmission [24,25] and their optical

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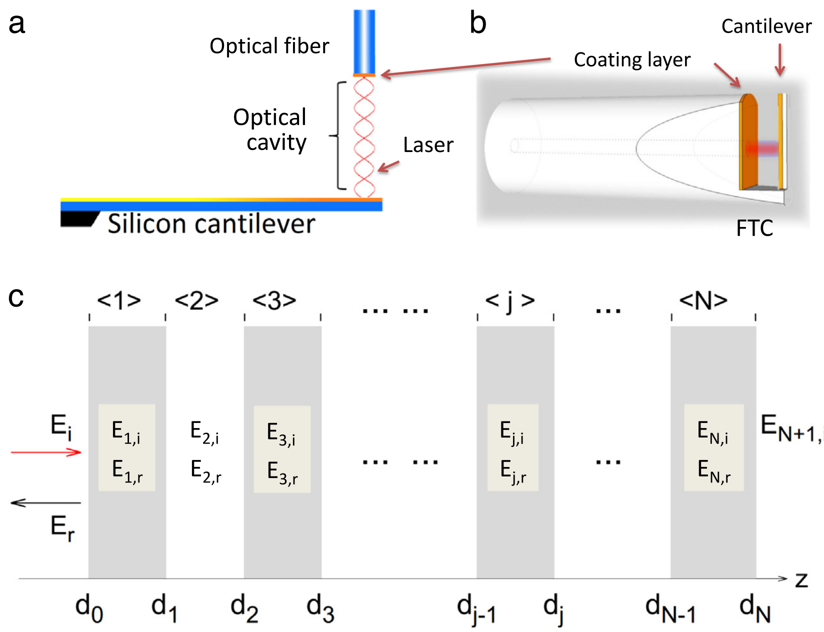

Fig. 1. Optical fiber-based sensors. A fiber can be directly pointed on cantilever which is coated by a metallic layer to create an optical cavity [11,12,15] (a) or it can be carved at the end to create a fiber-top cantilever [16] (b). The light intensity is enhanced because photons can go back and forth several times via the reflection with metallic surfaces before they leak out the cavity. Model of a multilayer system that is irradiated by a laser beam (c). The incident and reflective field amplitudes of the jth layer are $E_{j,i}$ and $E_{j,r}$. $E_{j,r} = 0$ for the last layer. Here, $N = 3$ we have $t_C = d_1 - d_0$, $t = d_3 - d_2$, and $E_{4,r} = 0$.

properties are generally examined using transfer matrices for each thin film, which allows total transmission/reflection to be obtained [25–27]. However, certain quantities for specific thin films, e.g., the field amplitudes inside the last film on the optical axis that are used to study the absorbed heat, or the field amplitudes immediately outside the film that are used to calculate the radiation pressure (RP), have not been evaluated to date. Therefore, the optimal configurations required for these multiple parallel thin films to optimize their mechanical and optical effects have not yet been determined. In this study, for the first time, we study the dependence of the optical properties of these optical multilayers on film thickness to allow optimal configurations to be achieved. It has been shown that a soft cantilever that is irradiated by a strongly localized force can have its vibration amplitude greatly changed [28], and that the modulated amplitude can be used to enhance the sensitivity of the cantilever when it is operated at higher order mechanical frequencies.

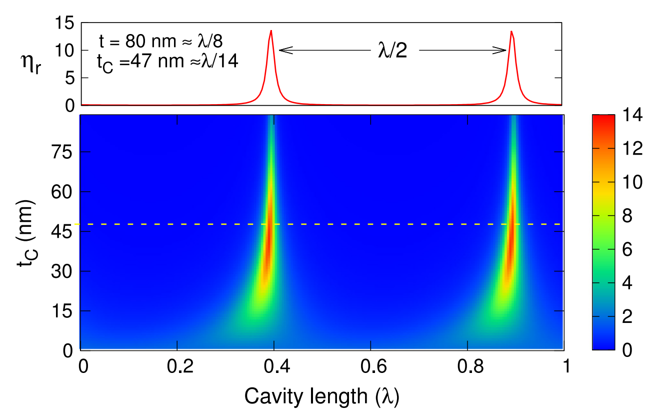

Fig. 2. Enhancement ratio η_r [see Eq. (8)] for $\lambda = 633$ nm and $t = 80$ nm for various coating thicknesses t_C. Greatest enhancement is seen for $t_C \sim 47$ nm (white dashed line) and this is shown on the top panel (red solid line).

2. Analytical method

A system of several layers arranged in parallel to form an optical cavity is shown in Fig. 1(c). A laser which has a wavelength λ is assumed to propagate perpendicularly to the multilayer surfaces. The parallel component of the wave vector [29–32] is vanished, $k_\parallel = k_x^2 + k_y^2 = 0$, and only the perpendicular part remains, $|\mathbf{k}| = k_\perp$. The wavenumber is reduced to be $k_0 = k_\perp = 2\pi/\lambda = \omega_{opt}/c$, where ω_{opt} is the optical frequency. The material of the coating layer (t_C) and of the cantilever layer (t) are assumed to be gold which has a dielectric function ϵ_{Au}. The cantilever back, which is made of silicon [Fig. 1(a)] or of glass [Fig. 1(b)], is assumed to have a unity dielectric function, $\epsilon_0 = 1$. Inside the Au layers, the wavenumber is $k_{Au} = sk_0$ where $s = \sqrt{\epsilon_{Au}/\epsilon_0}$ and $\epsilon_{Au[0]}$ is the dielectric function of Au[air]. The complex dielectric function of Au is $\epsilon_{Au}(\omega_{opt}) = \epsilon_b - \omega_{pl}^2/(\omega_{opt}^2 + i\gamma\omega_{opt})$, where $\omega_{opt} = 2\pi c/\lambda$ is the laser frequency, ϵ_b is the background dielectric constant, ω_{pl} is the bulk plasma frequency, γ is the nonradiative damping parameter, and c is the speed of light. By writing out all required equations for the electromagnetic fields and applying the boundary conditions for the jth boundary,

$$\epsilon_j \left[E_{j,i} e^{ik_j z} + E_{j,r} e^{-ik_j z} \Big|_{z=d_j} \right] = \epsilon_{j+1} \left[E_{j+1,i} e^{ik_{j+1} z} + \right.$$
$$\left. + E_{j+1,r} e^{-ik_{j+1} z} \Big|_{z=d_j} \right], \tag{1}$$

$$\epsilon_j \left[\frac{\mathrm{d}}{\mathrm{d}z} (E_{j,i} e^{ik_j z} + E_{j,r} e^{-ik_j z}) \Big|_{z=d_j} \right] = \epsilon_{j+1} \left[\frac{\mathrm{d}}{\mathrm{d}z} (E_{j+1,i} e^{ik_{j+1} z} + \right.$$
$$\left. + E_{j+1,r} e^{-ik_{j+1} z}) \Big|_{z=d_j} \right], \tag{2}$$

the field amplitudes $E_{j,i}$ and $E_{j,r}$ in every layer can then be obtained, where k_j is the wavenumber in layer j and $\epsilon_{j\{j+1\}}$ is the dielectric function. Using these thin films, the system can trap and enhance the magnitudes of the field intensities by several times [11]. The RP P_{rad} and the corresponding cavity-induced radiation force F_{rad} that are exerted on these thin films are usually calculated using the transfer matrix method. However, using of the multiplication of matrices gives lengthy expressions for the field amplitudes and it will be difficult to explicitly reveal the role of film thicknesses in field enhancement. Therefore, we