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Sensitive Detection of Nano-Scale Vibrations by the Metal-Coated Fiber Tip at the Liquid-Air Interface

A. J. Babajanyan, T. A. Abrahamyan, H. A. Minasyan, Kh. V. Nerkararyan

Abstract**—**Optical radiation emitted from a metal-coated fiber tip apex at liquid-air interface was measured. The intensity of the output radiation was strongly depend on the relative position of the tip to a liquid-air interface and varied with surface fluctuations. This phenomenon permits in-situ real-time investigation of nano-metric vibrations of the liquid surface and provides a basis for development of various origin ultrasensitive vibration detecting sensors. The described method can be used for detection of week seismic vibrations.

Keywords**—**Fiber-tip, Liquid-air interface, Nano vibration, Opto-mechanical sensor.

I. INTRODUCTION

THE combination of the optical fibers with the inherent benefits such as the light weight, small size, accessibility to confined space, immunity to electromagnetic and radio-frequency interference, wide bandwidth, and multiplexing capability and the interferometry with high-resolution, high-sensitivity provides the design and construction of the fiber optic interferometric sensors with many advantages over most conventional sensing techniques that have been widely exploited for the measurement and diagnostic of a large variety of system parameters [1], [2].

The sharpened fiber tip covered with a thin metal layer has interesting physical properties and was initially created as a probe for the scanning near-field optical microscope [3].

In this paper we discussed the behavior of light propagation in metal-coated fiber tip covered with a thin layer of a transparent dielectric liquid. We constructed an optical sensor based the proposed structure which can be a sensitive tool for measuring of the nano mechanical vibrations.

II. MODEL

The schematic structure of sharped optical fiber covered with metal layer and additional dielectric layer is shown in Fig. 1. Here, there are two waveguide channels that provide a guiding mode. The first, internal channel is the fiber core where the light initially propagates. The second, external channel is the dielectric layer where the light propagates toward the tip apex, so called surface plasmon polariton (SPP) mode [4]. If the metal layer is sufficiently thin, the modes of the internal and external channels can couple resonantly. As a result the light energy can transfer from one channel to the other only when the wave vectors of both modes match [5].

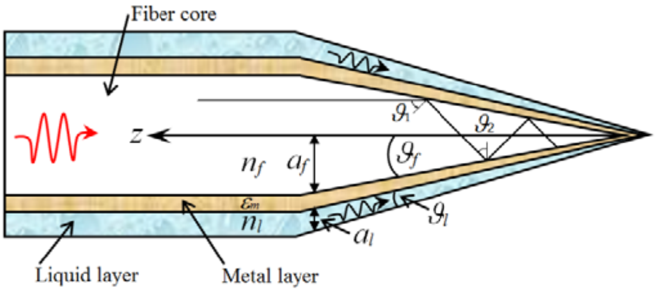

Fig. 1 The structure of sharpened fiber core covered by the metal layer and the liquid thin film where possible two modes coupling

The light wave propagates in the internal channel and reflects completely from the metal layer at the narrow end of the tip whereas the wave propagates in the external channel transmits from the tip apex. This property of the structure proves that the detected power is emitted from the external channel but not from the internal one. Thus, the energy transfers from the fiber into to the external liquid layer at a certain distance from the tip apex. To obtain resonant transmission, the wave vectors of both modes have to be equal for the certain thicknesses of the liquid layer [5].

III. EXPERIMENT

Experimentally the condition of resonant transmission can be simply realized if the thickness of the external dielectric layer varies along the tip axis. For example, the liquid meniscus formed around the metal-coated tip allows to continuously changing the thickness of external channel. The meniscus around the tip is formed when the tip bends a liquid surface during its motion at liquid-air interface.

The experimental setup is shown in Fig. 2. A LED laser radiation with 100 mW power operating at a 530 nm wavelength generates wave modes in the multi-mode optical fiber with a diameter of 100 µm. The other end of fiber was sharpened by the chemical etching method with a cone apex angle of about 16^{o} [6]. Fiber end was coated by the Au layer with 100 nm thickness. In the experiment as a liquid was used alcohol in transparent quartz cuvette which fixed to a single-axis piezo-stage with a 20 nm resolution. Relative motion of the tip to the liquid-air interface was done by moving the cuvette by means of the piezo-stage and the tip fixed during the measurements. The p-i-n photodiode with an amplifier is used for detection of optical power. At each step, the output

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power was measured 300 times and the mean power was taken for the investigation.

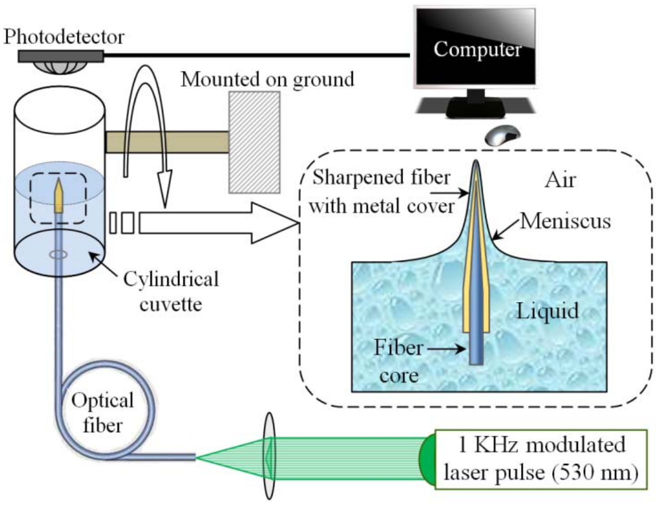

Fig. 2 The experimental setup of optical sensor for nano-vibration detection

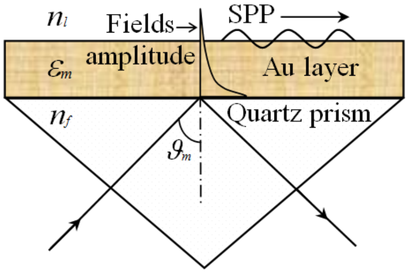

Fig. 3 The Krichman configuration for excitation of a SPP

IV. THEORY

In this section, the energy transfer from an optical fiber mode to the SPP mode is discussed. We consider the case when the radius of the fiber exceeds the light wavelength and the process of the wave propagation can be described by geometric optics. The incident wave propagates across the waveguide axis. If the opening angle of the cone is ϑ_f, then the incident angles, ϑ_m, are

$$\vartheta_m=\frac{\pi}{2}-(2m-1)\vartheta_f;\ m=1,\ 2,\ 3,...\ , \tag{1}$$

where $m=1$ corresponds to the first reflection, $m=k$ corresponds to the k^{rd} reflection, etc. The planar SPP excitation by means of the Krichman configuration [7]-[9] is similar to the above situation. Fig. 3 shows the SPP excitation by the Krichman configuration scheme. When the bending radius is much greater than the wavelength, the wave vector of the SPP can be determined by the formula for the planar SPP [8], [9]:

$$\beta_{SPP}=\frac{2\pi}{\lambda}\sqrt{\frac{n_l^2\varepsilon_m}{n_l^2+\varepsilon_m}}, \tag{2}$$

where β_{SPP} ($k_{SPP}=12\ \mu\text{m}^{-1}$) and λ ($\lambda=530$ nm) is the wave vector and the wavelength of the SPP, respectively. $n_l^2=\varepsilon_l$ and ε_m is dielectric permittivity of the surrounding liquid and metal, respectively.

Then, the incident angle for the excitation of the SPP is given by

$$\sin\vartheta_{SPP}=\frac{\lambda}{2\pi}\frac{k_{SPP}}{n_f}=\sqrt{\frac{n_f^{-2}}{\varepsilon_m^{-1}+\varepsilon_l^{-1}}}, \tag{3}$$

where n_l is the dielectric permittivity of the fiber core (fused quartz: $n_l=2.25$). A SPP will be excited when for some $m=1,2,3,...$ is satisfied and can be realized only under certain values of the opening angle of the cone, ϑ_f and the dielectric permittivity of the surrounding liquid, ε_l. If resonant excitation of a SPP is to be obtained on a metal surface [10], a thin layer of transparent dielectric is typically added. In our case, excitation is realized through vibration of liquid layer.

Let's consider that the cone is a sequence of cylinders with a continuously decreasing diameter; i.e., the transition to conical structure is realized by using an adiabatic approximation because the apex angle of the cone is not too large. For the cylindrical waveguide wave vector, each mode can be determined as [11]

$$\beta_{f,l}=\sqrt{n_{f,l}^2\frac{\omega^2}{c^2}-\chi_{f,l}}, \tag{4}$$

where $n_{f,l}$ is the refractive index of the medium (index f and l corresponds to the fiber and the liquid, respectively), ω is the cylindrical wave frequency ($\omega=2\pi c\lambda^{-1}$), c is the speed of light, and $\chi_{f,l}$ is the parameter that determines by the transverse profile fields of the mode. From the general theory of the guided waves, it follows that $\chi_{f,l}$ is inverse proportional to the size of the region of the wave localization:

$$\chi_{f,l}=\frac{\alpha_{f,l}}{a_{f,l}}. \tag{5}$$

Here $a_{f,l}$ is the typical size of the localization regions for the internal and external channels and $\alpha_{f,l}$ is the constants which can be determined from the theory ($a_{f,l}\cong 1$). In the case of a conical structure (Fig. 1, $\vartheta_{f,l}<<1$), the dependence of $a_{f,l}$ on the z coordinates must be $a_{f,l}=\vartheta_{f,l}z$.

From the theory of coupled modes, the effective transfer of wave energy from one mode to the other is possible when their wave vectors are equal ($\beta_f = \beta_l$) in the large region of the propagation [12]. In the considered case this is true if

$$\begin{cases} n_f = n_l, \\ \dfrac{\alpha_f}{\vartheta_f^2} = \dfrac{\alpha_l}{\vartheta_l^2}. \end{cases} \tag{6}$$

The first condition in (6) can be realized by the proper choice of the liquid. In our experiment, as a liquid we used alcohol with $n_l = 1.47$, whereas for the fiber core $n_l = 1.46$. The second condition can be realized by changing the angle ϑ_l. Angle ϑ_f decreases when the tip goes out from the liquid into the air. The conditions in (6) can be realized at the definite position of the tip relative to the liquid-air interface and then the strong enhancement of the output radiation is registered.

V. RESULTS AND DISCUSSION

Fig. 4 shows the changing behavior of the output optical signal during the tip movement along liquid-air interface. When the tip goes out from the liquid into the air, it bends the liquid surface and gradually a meniscus is formed around the sharpened tip. At some position of the tip, a strong enhancement of output radiation was registered which caused by the resonant transfer of the wave energy from the fiber to the liquid medium mode.

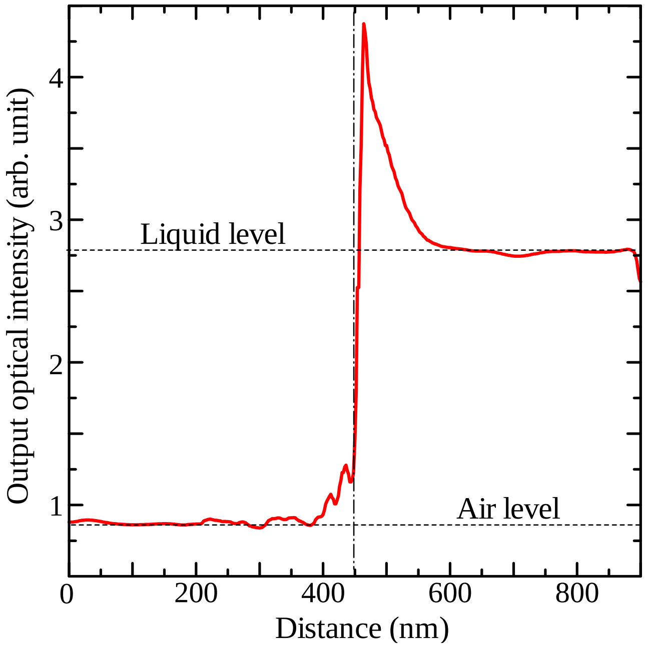

Fig. 4 The detected optical signal when tip crossed the air-liquid interface

The peak power of output radiation essentially depends on the thickness of a metal layer through which the light radiation passes. The experimentally measured power of peak radiation was about 50 μW. This process can be realized at certain forms, thicknesses, and material characteristics (dielectric permittivity) of the liquid meniscus.

The strong dependence of this effect on the form and dielectric permittivity of the external dielectric layer provides a basis for development of various types of sensor. Due to this dependence it is possible to register nanometric vibrations of the liquid surface which can have useful applications in detection and investigation of weak seismic vibrations. For example, if fix the tip at the certain position in the vicinity of the peak, even the weak vibrations of a liquid surface appreciably will change the output power. From the received dependence of output power on time, it is not difficult by numerical methods to define a spectrum of output radiation.

Clearly, those characteristic frequencies of this spectrum will be frequencies of vibration of a liquid surface. It is possible to assume that the received resonant frequencies are frequencies of a building where the experiment is made.

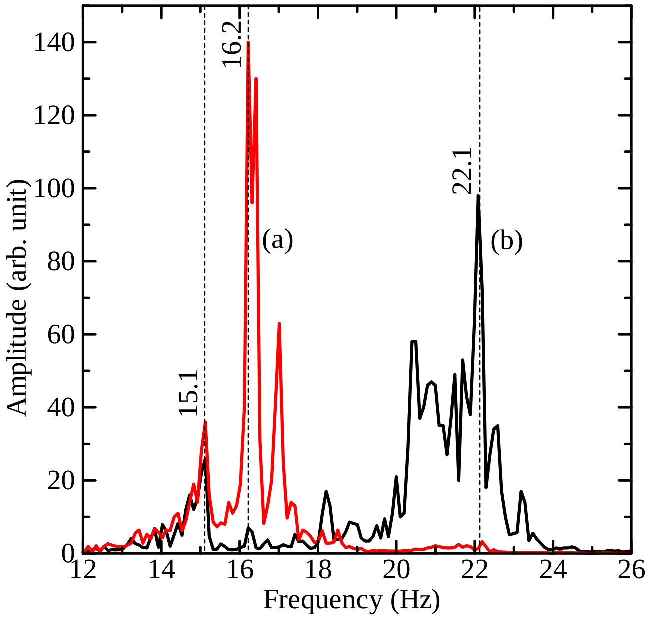

Fig. 5 The vibration spectra of four floor building detecting by optical sensor: cylindrical form cuvette filled with (a) half and (b) full alcohol

The sample of building vibration frequencies spectra is shown in Fig. 5. The fixed peak at 15.1 Hz was correspond building vibration while each resonator (cuvette with half or full filled liquid) of the sensor has his own resonant behavior with highest peak at 16.2 Hz and at 22.1 Hz for half and full filled cuvette, respectively. The form of cuvette (cylindrical, spherical, rectangular) change the total vibration spectra of sensor (results not shown here) but the building characteristic vibration peak was clearly distinguished for each case.

Note that they sensor *Q*-factor is almost same; up to 120 for both half and full filled cuvette cases. Even though the *Q*-factor of the investigated cavity is modest, the ultra-small mode volume *V* can potentially lead to a significant enhancement of the measurements rate. The smallest detectable change in the vibration amplitude based on a criterion of measurements signal-to-noise ratio is about 50 nm.

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VI. CONCLUSIONS

We have described a novel concept for detecting nano vibrations at liquid-air interface which is based on the effect of light wave energy transfer from the fiber core mode into the external liquid layer mode in the metal-coated fiber tip surrounded with a liquid meniscus.

The described method can be used for detection of week seismic vibrations. The investigation of weak vibrations at liquid-air interface can be applied in study of hydrodynamic processes such as the modeling of the processes occurring on the water surface of the Earth.

Another application of this detection method can be the gas sensors if metallized fiber tip is covered with an external solid dielectric layer. Adsorbed gas molecules will change the effective refractive index of the external dielectric layer with further stimulation of the energy transfer between two waveguide modes and enhancement of the output signal.

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