A novel optical multilayer hydrophone with a triangular pyramid substrate

Suyong Wu (吴素勇)*, **Xingwu Long (龙兴武)**, **Kaiyong Yang (杨开勇)**, **and Yun Huang (黄 云)**

Department of Optoelectronic Engineering, College of Optoelectronic Science and Engineering,
National University of Defense Technology, Changsha 410073, China

**Corresponding author: sywu2001@163.com*

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A novel concept for an optical multilayer ultrasonic hydrophone with the sensing film deposited on a triangular pyramid glass substrate is proposed. Using the calculation model for the spectral coefficients' derivatives of a dielectric multilayer optical coating, the acousto-optic sensitivity characteristic of the hydrophone is analyzed with different measurement laser polarizations and incident angles. We present a reasonable method and adjusting strategy for the optimum working point selection of the ultrasound measurement. Analytic results show that the novel hydrophone possesses all the other merits of a plate glass substrate optical multilayer hydrophone but with improved detection sensitivity. A longer measurement time without distortion decreases the difficulty of high frequency signal circuits. Spatial split of the ultrasound signal caused by the substrate's triangular pyramid roof simplifies the spatial spot area correction, which contributes to the accurate calibration of the hydrophone's wideband frequency response.

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The concept of optical coating as sensing element for ultrasound detection is used to construct high sensitivity fiber-optic hydrophones[1−3], with Nb_2O_5 dielectric layers[1], titanium metal layers[2], and 15-layer all-dielectric narrowband filters[3]. Acoustic measurement is mainly based on the elastic deformation and elasto-optic effect of the optical coating and the fluid refractive index variation around the fiber tip by the incident ultrasonic wave. Due to the influence of edge diffraction wave and lateral resonance effect of the fiber tip[4,5], the frequency response of the fiber-optic hydrophone shows a high frequency resonance peak and a slight periodic modulation. Although the reduction of resonance peak can be caused by a disturbance in the radial symmetry of the fiber tip[4] or by implementing a tapered fiber with a tip diameter of approximately 7 μm[6], it is difficult to eliminate the inherent frequency response non-uniformity of fiber-optic hydrophones.

Utilizing a large diameter ultrasonic probe instead of a narrow fiber tip to avoid the acoustic resonance and edge diffraction from causing waveform distortion is a promising method[7,8]. The representative work was a plate glass substrate optical multilayer hydrophone presented by Wilkens *et al.*[9−12]. The sensing element was a 19-layer high finesse Fabry-Perot narrowband filter film deposited on a 30-mm-diameter glass plate by vacuum sputtering technique, consisting of two dielectric materials of Nb_2O_5 and SiO_2 with a total thickness of 1.9 μm[9]. This hydrophone basically offered high temporal and spatial resolution and high probe durability together with a constant frequency response ranging from 1 to 75 MHz[10]. The existing defect is a sensitivity problem, which is comparably lower than that of the polymer fiber-optic hydrophone[13] and significantly an order lower than that of the polyvinylidene fluoride (PVDF) membrane hydrophone with a large diameter[10]. Promising methods to improve sensitivity include large film layer, optimum selection of working points, and controlling the intensity noise of the laser and optical detection pass[3,10]. In this letter, we present a novel triangular pyramid glass substrate instead of the glass plate used in Ref. [10]. The novel hydrophone structure can completely utilize the acousto-optic sensitivity characteristic with an incident angle of S-polarization light to adjust the working point to maximum sensitivity, which can improve the hydrophone's receiving sensitivity without adding the sensing film layer number.

An optical multilayer hydrophone with a glass plate substrate is well-suited for the use as a reference detector for secondary calibrations of hydrophones and fiber-optic ultrasonic sensors considering its constant wideband frequency response, high temporal and spatial resolution, and high probe durability[10]. However, its significantly lower sensitivity compared to PVDF

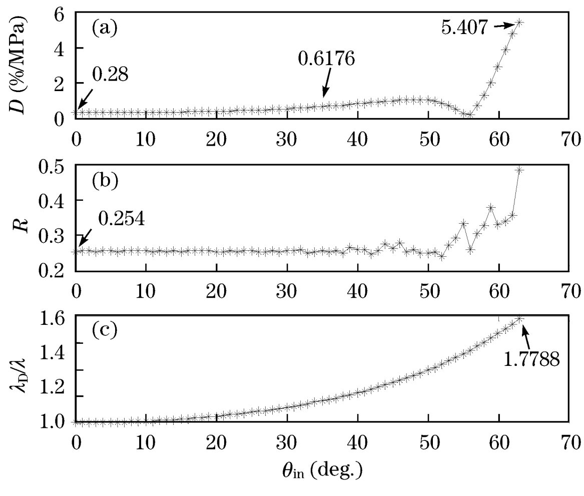

Fig. 1. (a) Maximum acousto-optic sensitivity D, (b) reflectance R, and (c) operation laser wavelength λ divided by the design wavelength λ_D of the optimum working point with incident angle θ_{in} for S-polarization light of a 19-layer narrowband filter.

membrane hydrophones with large diameters limits its application in low intensity ultrasonic fields.

Due to the mismatch of the refractive index of air and glass plates, following the Snell law, the actual incident angle of the sensing narrowband filter film is limited at $\arcsin(1/n_g)$ (i.e., 42.5°, while the refractive index of glass n_g=1.48). To solve the sensitivity problem, we do not consider the maximum incident angle limitation caused by the substrate structure. According to the layer parameters and elasto-optic coefficients of the 19-layer narrow band filter shown in Ref. [10], we recompute the maximum acousto-optic sensitivity with the incident angle for different polarization lights based on the calculation model for spectral coefficients' derivatives of the dielectric multilayer optical coatings[14−16]. Under the first order approximation, the calculation expression for acousto-optic sensitivity is

$$D = \left|\frac{\Delta R}{p_{\rm in}}\right| = \left|\frac{p}{p_{\rm in}}\frac{\Delta R}{p}\right|$$
$$= \left|\frac{p}{p_{\rm in}}\left(\sum_{i=1}^{N}\left(\frac{\partial R}{\partial n_i}\frac{\Delta n_i}{p} + \frac{\partial R}{\partial d_i}\frac{\Delta d_i}{p}\right) + \frac{\partial R}{\partial n_{N+1}}\frac{\Delta n_{N+1}}{p}\right)\right|$$
$$= \left|1.8\left(\sum_{i=1}^{N}\frac{1}{\rho_i v_i^2}\left(\frac{n_i^3 p_{12i}}{2}\frac{\partial R}{\partial n_i} - d_i\frac{\partial R}{\partial d_i}\right) + \frac{\partial R}{\partial n_{N+1}}\frac{\Delta n_{N+1}}{p}\right)\right|, \quad (1)$$

where D denotes the acousto-optic sensitivity of the sensing film; $p_{\rm in}$ is the incident free-field ultrasound pressure; ΔR is the resulting reflectance change of sensing film; p is the actual ultrasound pressure in front of the sensor; N is the layer number of the sensing film; n_i, d_i, ρ_i, and v_i are the refractive index, physical thickness, density, and sound velocity of the ith layer, respectively. After careful calculations, we plot the maximum acoustic-optic sensitivity, the reflectance and operation laser wavelength divided by the design wavelength of the optimum working point with the incident angle for S- and P-polarization lights respectively in Figs. 1 and 2. Maximum incident angle is the total internal reflection critical angle at the glass-water interface where the sensing narrowband filter fails and becomes a high reflector. Numerically, this critical angle is $\arcsin(n_w/n_g)$, i.e., 63.89°, whereas the refractive index of water n_w takes the value of 1.329 as given in Ref. [10].

From Fig. 2, the acousto-optic sensitivity of P-polarization light decreases monotonically with the incident angle, which coincides with the results in Ref. [10]. As shown in Fig. 1, the acousto-optic sensitivity of the S-polarization light increases with the incident angle until a maximum at 49°, decreases to a minimum (not zero) at 57°, and then rapidly increases to much higher sensitivity values until the maximum critical angle. The new sensitivity law of the S-polarization light coincides with the monotonic increasing law listed in Ref. [10] at small incident angles, but adds much more useful information at large incident angles, particularly for the improvement of sensitivity.

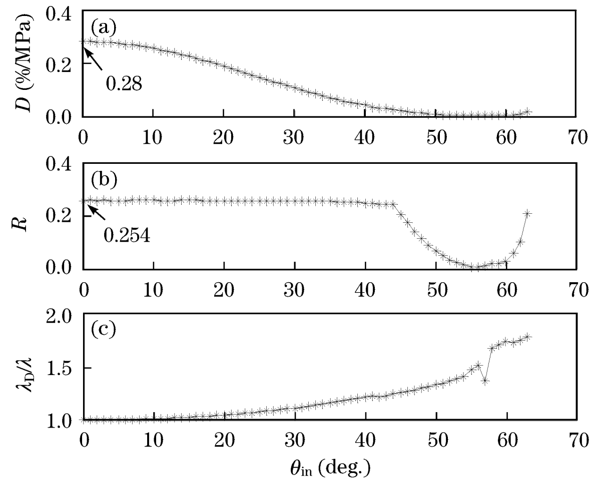

Fig. 2. (a) Maximum acousto-optic sensitivity D, (b) reflectance R, and (c) operation laser wavelength λ divided by the design wavelength λ_D of the optimum working point with incident angle $\theta_{\rm in}$ for P-polarization light of a 19-layer narrowband filter.

The difference in absolute value of the acousto-optic sensitivity D and optimum operation laser wavelength compared with Ref. [10] is caused by the inaccurate computation of the optimum working point. In Ref. [10], the optimum working point is approximately calculated at a reflectance value of 0.25, whereas in our calculations, the optimum working point is accurately determined by the maximum acousto-optic sensitivity value computation based on the precise calculation model for spectral coefficients' derivatives of dielectric multilayer optical coatings[14−16]. For the narrowband filter, a relatively small change in the wavelength causes an obvious change in the reflectance and corresponding sensitivity value. From Figs. 1(b) and 2(b), the reflectance of the optimum working point deviates the value of 0.25 in Ref. [10] and fluctuates slowly around the value of 0.254 at small incident angles and fluctuates rapidly at larger incident angles. The small increase of sensitivity value at 35° from 0.387 in Ref. [10] to 0.6176 in Fig. 1(a) is obtained by the accurate determination of the optimum working point.

To explain the special characteristic of acousto-optic sensitivity with an incident angle, we make a theoretical analysis of the all-dielectric narrowband filter film. According to the film optics theory, when the incident angle increases, the maximum transmittance in the pass band decreases for both polarization lights, and the half-width of the high transmittance band increases for the P-polarization light and decreases for the S-polarization light. For the P-polarization light, these two effects superimpose constructively with the result of a decreasing reflectance slope when the incident angle increases. Thus, sensitivity D decreases monotonically with the incident angle. For the S-polarization light, these two effects superimpose destructively with a complicated result. The effect of band narrowing prevails at small incident angles with an increasing reflectance slope until a maximum. The maximum transmittance then obviously decreases at the middle incident angles with the reflectance slope decreasing to a minimum where these two effects completely counteract. At large incident angles, the effect of the band narrowing increases rapidly with a much higher and increasing reflectance slope until it reaches zero at the total internal critical angle.

The unexpected characteristic of the acousto-optic sensitivity with an incident angle for S-polarization is of important significance for the improvement of detection sensitivity and the adjustment of the optimum working point of the optical multilayer hydrophone. Thus, to adjust the hydrophone to work at maximum acousto-optic sensitivity, we should change the glass substrate's roof geometric structure to increase the incident angle, such as manufacturing a wedge or arc structure. Given that a small difference exists between the design sensing narrowband filter film and the deposited film sample, an additional adjustment of the incident angle is needed to precisely locate the optimum working point. A triangular pyramid glass substrate incorporates wide incident angle range and convenience of optical path adjustability, alignment, and stability together, which is very favorable for becoming an ideal substrate.

Figure 3 is the setup sketch of this novel triangular pyramid optical multilayer hydrophone with obliquity angle of 63°. According to Fig. 1(c), the design wavelength should be set to 1.7788 times that of the detection laser wavelength to make the laser wavelength the optimum working wavelength at an incident angle of 63°. If a He-Ne laser of 633-nm wavelength is also used to detect ultrasound, the film thickness should increase due to the increase of the design wavelength. Numerically, the total thickness is 3.126 μm, which is still much thinner than the ultrasonic wavelength and is effective in avoiding thickness resonance effects. From Fig. 1(a), when the incident angle of the laser is adjusted from 35° to 63°, the acousto-optic sensitivity improves from 0.6176 to 5.407, i.e., 8.8 times, approximately an 18.9 dB improvement in the detection sensitivity of the hydrophone. If compared to the acousto-optic sensitivity of 0.387 of Ref. [10], the improvement is even higher by 14 times. This obvious improvement in sensitivity is obtained just by changing the plate substrate structure to a triangular pyramid substrate structure. This change is easy to realize and does not add much to the manufacturing cost.

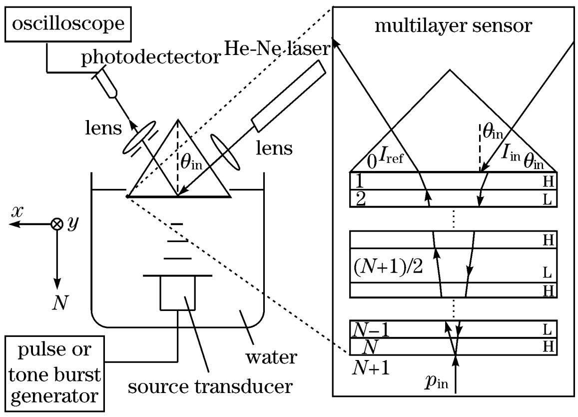

Fig. 3. Optical multilayer hydrophone setup with a triangular pyramid glass substrate. H and L represent high and low refractive index layers, respectively.

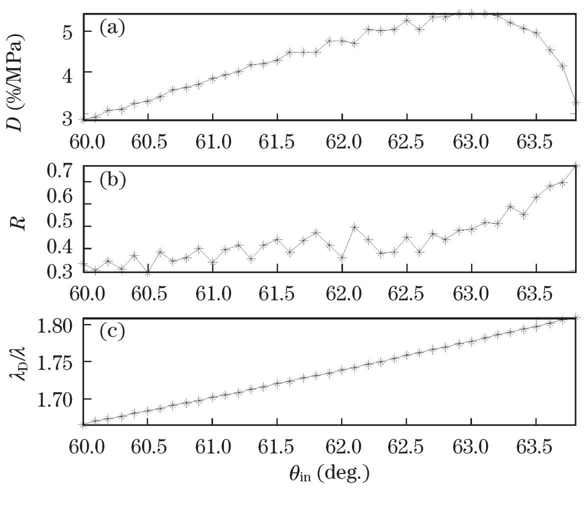

Fig. 4. (a) Maximum acousto-optic sensitivity D, (b) reflectance R, and (c) operation laser wavelength λ divided by the design wavelength λ_D of the optimum working point with incident angle θ_{in} around 63° for S-polarization light of a 19-layer narrowband filter.

For the actual working point slightly adjusting to optimum working point, a much denser plot of reflectance of the optimum working point with an incident angle near 63° should be useful to compare the direct current (DC) output intensity of the photodetector. Figure 4 shows the maximum acoustic-optic sensitivity, the reflectance and operation laser wavelength divided by design wavelength of the optimum working point with an incident angle between 60° and 63.8° for the S-polarization light. If the central transmittance wavelength of the filter sample at normal incidence slightly decreases, then the incident angle should decrease as well, as presented in Fig. 4(c). The corresponding photodetector output DC value variation can be seen in Fig. 4(b). The interesting degradation of sensitivity with an incident angle from 63° to 63.8° found in Fig. 4(a) coincides with the above theoretical analysis as the maximum transmittance decreases rapidly to zero at the total internal reflection critical angle of 63.89°.

Further advantages are found with the triangular pyramid substrate structure besides the large improvement in sensitivity. The thickness of the triangular pyramid substrate is comparable with its lateral dimension, which can extend the measurement time without the waveform distortions caused by the acoustic reflections from the rear roof of the substrate. Take the plate substrate in Ref. [10] with a diameter of 30 mm and a thickness of 6.5 mm as an example. When changed to triangular pyramid substrate, the path length of back-reflection ultrasound to sensing film becomes at least 30 mm. Hence, the time for acoustic reflections from the rear roof to arrive at the sensing film extends from ~2.2 μs to at least 5.2 μs (sound velocity in glass is 5800 m/s). The larger the diameter of the substrate, the longer the measurement time without distortions. Longer measurement time can lower the difficulty of high frequency signal process circuits of the outputs of the photodetector. Meanwhile, during long time measurement application fields, the reflection of the incident ultrasound at the rear roof of the triangular pyramid substrate is spatially separated from itself, except for the normal incident ultrasound at the center of the sensing film. An ultrasound beam of finite dimensions incoherently superimposes its reflection from the rear roof of the hydrophone substrate. Thus, the spatial averaging correction can be easily modeled, which benefits the accurate calibration of the wideband frequency response of the novel optical multilayer hydrophone.

At present, the novel optical multilayer hydrophone is being manufactured. A robust and rugged all-dielectric narrowband filter film can be obtained by the vacuum ion sputtering deposition technique in the near future. Although verified by relative research individuals in short-term[13] and long-term[10], detailed experiments on the performance of the sputtered film under the soak and corrosion of water is the following central work. This is important for the lifetime assessment and durability experiments of the optical multilayer hydrophone. Another problem that needs to be solved is the accurate manufacture of the large obliquity angle of substrate, which is critical to realize and adjust the optimum working point.

In conclusion, a novel concept of an optical multilayer ultrasonic hydrophone is put forward with the sensing film deposited on a triangular pyramid glass substrate. Using the calculation model for spectral coefficients' derivatives of the dielectric multilayer optical coating, the acousto-optic sensitivity characteristic of hydrophone is analyzed with different measurement laser polarizations and incident angles. By selection of the optimum working point, the sensitivity of the optical multilayer hydrophone can be elevated without adding the layer number of sensing film. Longer measurement time without distortion resulting from its triangular pyramid substrate structure decreases the difficulty of high frequency signal circuits. Spatial split of ultrasound signal caused by the substrate's triangular pyramid roof simplifies the spatial spot area averaging correction, which benefits the accurate calibration of the hydrophone's wideband frequency response.

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