Estimation of surface plasmon resonance conditions in optical sensors according to the Kretschmann scheme

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To date, the question of the thermal effect of laser radiation on the "gold nano layer – water" system in sensors according to the Kretschmann scheme remains unexplored. But such a study is very important, since, on the one hand, water is the main component of the sensitive element of the sensor, and on the other hand, it is known [1, 2] that the effect of the laser radiation flux on a metal nano layer can lead to its significant heating, and respectively, to the heating of adjacent layers of water. Since the dielectric properties of water significantly depend on the wavelength and temperature [3], then under the influence of temperature the sensory effect can shift relative to the expected one along the wavelength [4] and the resonance angle of incidence [5, 6, 7]. Given this, it is important to find conditions under which the effects of temperature can still be neglected.

On the other hand, the sensory response to heating of the gold nano layer and adjacent layers of water can be used to directly measure the magnitude of the laser flux. Such a measurement can be important for determining the modes of laser radiation in terms of the radiation flux, rather than energy or power. This will allow to coordinate theoretical studies which use the terms of flux with experimental studies that use the power emitted by a laser, or the energy that is pumped into a pulse.

The work is devoted to these questions. In particular, the issues of the influence of heating the "gold nano layer – water" structure on the sensory effect, the identification of conditions under which the effect of temperature can still be neglected, and the analysis of the conditions for creating a direct measurer of the laser radiation flux.

Dependence of surface plasmon resonance wavelength on temperature

Scheme of the sensor in the Kretschmann configuration [8]:

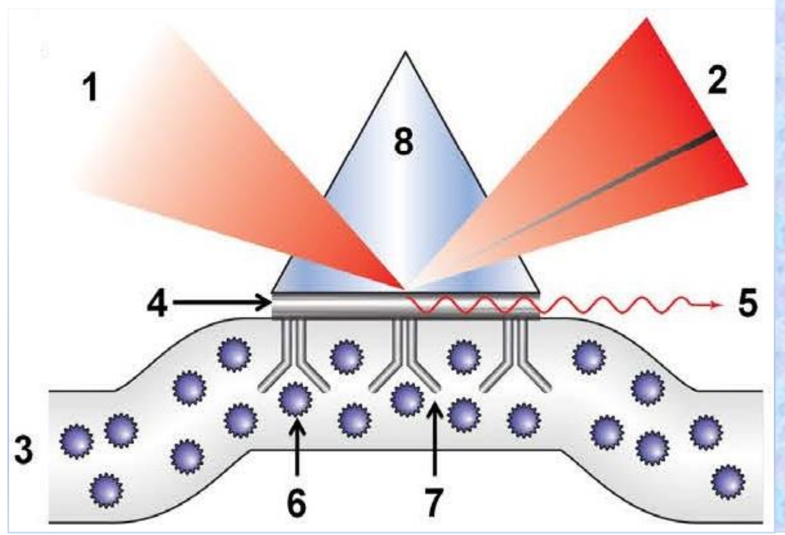

Fig. 1.
1 – exciting light;
2 – reflected light;
3 – the medium being analyzed (analyte);
4 – metal film;
5 – surface plasmon;
6 – ligand (or adsorbed molecular structure);
7 – receptor (or adsorbent);
8 – dielectric prism with a high refractive index.

In this scheme, the wavelength of the surface plasmon resonance λ_{pr} is determined by the equality [4]: $\lambda_{\mathrm{pr}} = \lambda_{\mathrm{p}}\sqrt{1+n^2}$. Here n is the refractive index of the medium (position 3 in Figure 1). In our case, the medium is water. The factor λ_{p} is the wavelength of plasma oscillations. For gold, according to our estimates, $\lambda_{\mathrm{p}} = 325.6$ nm. For the refractive index of water, the formula was used, the structure of which has the form [3]:

$$n(\lambda, t) = 1.3208 + \sum_{\alpha=0}^{\alpha=3}\sum_{\beta=0}^{\beta=3}\left(A_{\alpha\beta}\, t^{\beta}/\lambda^{2\alpha}\right). \qquad (1)$$

The coefficients $A_{\alpha\beta}$ are completely denoted in [3], where $A_{00} = 0$. For λ_{pr} the transcendental equation is obtained: $\lambda_{\mathrm{pr}} = \lambda_{\mathrm{p}}\sqrt{1+n^2(\lambda_{\mathrm{pr}}, t)}$. This equation was solved graphically-numerically and the dependence of the wavelength of surface plasmon resonance on temperature was obtained:

$$\lambda_{\mathrm{pr}}(t) = 543.2 - 0.01\, t - 0.0003\, t^2\,. \qquad (2)$$

When the water temperature changes from 0ºC to 100ºC, the wavelength λ_{pr} changes by 4 nm (from 543.2 to 539.2).

Conditions under which temperature effects can be neglected. Device for measuring the flow of laser radiation

The gold layer (position 4 in Figure 1) under the influence of the flow of laser radiation, without taking into account heat exchange, is heated according to the equality [1, 2]:

$$t(q) = t_0 + 2q\sqrt{\tau}/\sqrt{\pi\rho C_{\mathrm{v}}\Lambda}\,. \qquad (3)$$

Here t_0 =20ºC, q is the radiation flux (erg/cm^2 s), $\tau = 60$ s is the exposure time, $\rho = 19.23\ \mathrm{g/cm^3}$ is the gold density, $C_{\mathrm{v}} = 1.29\cdot10^6\ \mathrm{erg/(g\cdot K)}$ is its specific heat capacity, $\Lambda = 3.18\cdot10^7\ \mathrm{erg/(cm\cdot K\cdot s)}$ is its thermal conductivity. This formula allows finding the maximum possible flow q at which the water temperature reaches 100ºC: $q = 2.5\cdot10^8$ erg/cm^2 s. Substituting (3) into (2), we can construct the dependence $\lambda_{\mathrm{pr}}(\lg(q))$. This is shown in Figure 2. The figure shows that up to the value of $q = 10^6\ \mathrm{erg/cm^2\,s}\ (10^{-1}\ \mathrm{W/cm^2})$ the plasmon resonance wavelength does not change. That is, before flows of such magnitude, the effect of temperature on the readings of the water-gold sensor is absent. It is interesting to note that this flux value corresponds to the flux of solar radiation. The temperature effect can be neglected even up to the flows $q = 10^7\ \mathrm{erg/cm^2\,s}\ (1\ \mathrm{W/cm^2})$. This is true for 60 s exposure. For other exposures, according to (3), the values of such flows will be another. Such studies make it possible to determine the ranges of absence of the temperature influence for the selected exposure time when using a specific sensor.

Figure 2 also shows that starting from the flow $q = 10^7\ \mathrm{erg/cm^2\,s}\ (1\ \mathrm{W/cm^2})$ to the value $q = 25\cdot10^7\ \mathrm{erg/cm^2\,s}\ (25\ \mathrm{W/cm^2})$ there is a strong dependence of the wavelength on the flow. This can be used as a direct measurer of radiation flux in the range 1÷25 $\mathrm{W/cm^2}$. By using other dielectrics instead of water, and electronic registration schemes that reduce exposition time, this range can be significantly expanded.

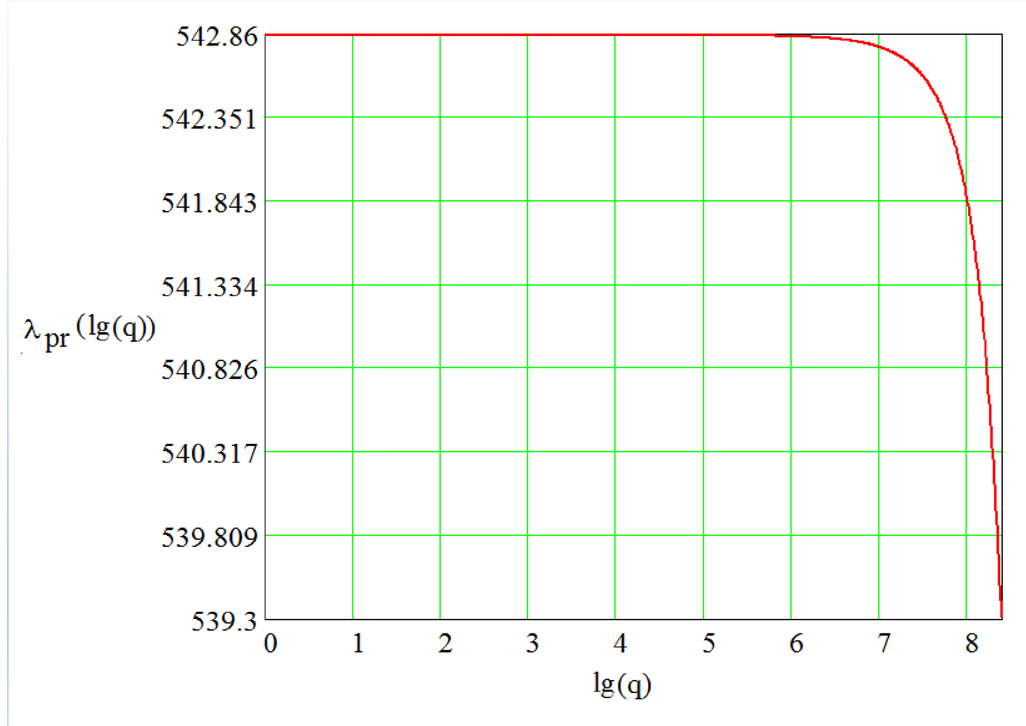

Fig. 2. Dependence of the plasmon resonance wavelength on the laser radiation flux.

Resonant angle of incidence and registration of the effect

To clarify the possibility of observing the temperature effect: wavelength changes of the plasmon resonance by 4 nm, the change in the angle of incidence of the plasmon resonance were analyzed. Using the results given in [5, 6, 7], after some transformations, the equality for calculation was obtained:

$$\alpha_{\mathrm{res}}(t) = \frac{180}{\pi}\arcsin\left(\frac{1}{n_{\mathrm{p}}}\sqrt{\frac{n^2\big(\lambda_{\mathrm{pr}}(t), t\big)}{1+\dfrac{n^2\big(\lambda_{\mathrm{pr}}(t), t\big)}{\mathrm{Re}(\varepsilon_{\mathrm{Au}})}}}\right).$$

Here $n_{\mathrm{p}} = 2.425$ is the refractive index of the prism (position 8 in Figure 1). The refractive index of water $n(\lambda, t)$ is defined in (1), and the dependence $\lambda_{\mathrm{pr}}(t)$ is defined in (2). $\mathrm{Re}(\varepsilon_{\mathrm{Au}}) = -5.1761$. Using the dependence (3) in the definition of the resonant angle, it is possible to construct the dependence of this angle on the logarithm of the flow. This relationship is shown in Figure 3. The figure shows that the change in angle is ~ 1º. Such a deviation may cause a measurement error.

Conclusions

It is established that the influence of water temperature on the wavelength of surface plasmon resonance in the structure "prism - golden nano layer - water" is 4 nm (from 543.2 to 539.2 nm).

It is shown that this change corresponds to a change in the angle of incidence by ~ 1º, which is a very noticeable sensory effect that cannot be neglected.

Evaluation of the maximum value of the radiation flux at which the effect of temperature can still be neglected performed: at exposure duration of 60 s, it does not exceed 1 W / cm².

On the basis of researches the possibility of creation of the direct measuring instrument of a radiation flux in the range of 1 ÷ 25 $\mathrm{W/cm^2}$ is shown.

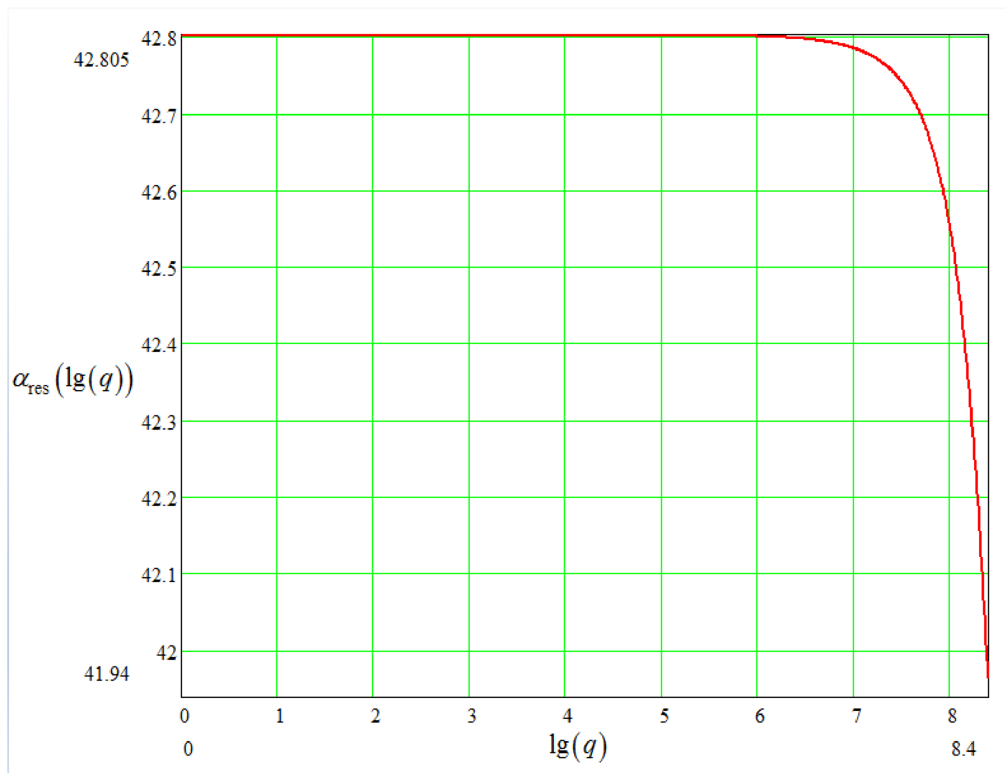

Fig. 3. The dependence of the resonant angle of incidence on the flux of laser radiation.

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