Static sensitivity calculation of a novel fiber optic biosensor

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Received September 16, 2008

A novel structure of fiber optic biosensor and its principle are introduced. The sample is detected in microchannels of several microns diameter in fiber optic biosensors. The relation between the optic fiber tapered angle and the fluorescence incident angle is calculated in signal receiving part. As the sensor is a zero-order system, calculating formula of the static sensitivity is derived. When ZnSe nano-crystalline cluster is used for marking the molecules, the static sensitivity for fiber optic biosensors is calculated. At the same time, the relation between the static sensitivity and the ratio of exciting wavelength to fluorescence wavelength is presented.

OCIS codes: 160.2540, 060.2370, 280.1415, 350.3950.

doi: 10.3788/COL20080612.0922.

With the development of micro-electro-mechanical system (MEMS) fabricating technology, microsensors used for detecting some components in air and solution become more and more smart and smaller. Micro total analysis system (MTAS) processed in a chip is a potential technology[1]. At present, the optic fiber used for transmission media and optics sensitive component of sensors emerge a lot of technologies such as the optic fiber humidity sensors, the fiber torsion sensors, the fiber optical evanescent wave biosensors, the fiber optic immunoassay biosensors, etc.[2−5]. The technology for fiber optic biosensors is rising for high sensitive microanalysis technology and can implement long-distance real-time measurement. Fiber optic biosensors can be widely applied in environment monitoring[4], quality control for food and drug, biosafety, and so on.

Presently, fiber optic biosensors have been largely researched and developed[6−8]. Technology and results from Naval Research Laboratory (NRL) of America and Research International Company are in the state of the art all over the world. Meanwhile, some of them have been equipped in armies. Study of fiber optic biosensors begins later in China. But recently, many research institutions have expressed concern about it and obtained many great results. Generally, although fluorescence can be used for receiving the light of detecting signal, it may cause many problems, such as weak signal, large noise, and mismatch of the optic fiber mode, and so on[9].

Microchannels used as detecting room can decrease the size of fiber optic biosensors and consumption of sample. Particularly, some experiments which need extract blood time after time in body will increase the pain of patients. Semiconductor nano-crystalline cluster used for detecting molecules can enhance the fluorescent signal largely. Multimode optical fiber used as medium of input and output can reduce signal noise. In this letter, a novel structure of fiber optic biosensors is designed and analyzed. The relation between the optic fiber tapered angle and the fluorescence incident angle in signal receiving part is calculated. When the sensor is a zero-order system[10], calculation formula of static sensitivity is derived.

Exciting light and received fluorescence are implemented by a multimode optic fiber. The end of the exciting optic fiber part is made by scraggy cone surface and modified by biologic methods. Part of the receiving fluorescent fiber is also made by cone surface. Part of the exciting optic fiber and the receiving fluorescent fiber are jointed by an optic fiber core. The optic fiber is placed in microchannels of several microns diameter. Construction of fiber optic biosensors is given in Fig. 1.

After the solution of detecting molecules marked with fluorescence is in microchannels, molecules marked with fluorescence can be adsorbed into the cone surface of part of the exciting optic fiber. When a light excites fluorescent molecules, fluorescence is received and transmitted in the receiving fluorescent fiber part. Fiber optic biosensors are constituted by two parts: one is molecules identifying and exciting fluorescent molecules, and the other is receiving fluorescence and transmission. The molecules identifying and exciting fluorescent molecules are made by scraggy cone surface as shown in Fig. 1, which can irradiate easily light and excite fluorescent molecules. In addition, such construction can easily adsorb near detecting molecules of cone surface and luminous efficiency of fluorescent molecules can be strengthened. Construction of the receiving and transmitting fluorescent fiber is shown in Fig. 2. The receiving fluorescent part is made of

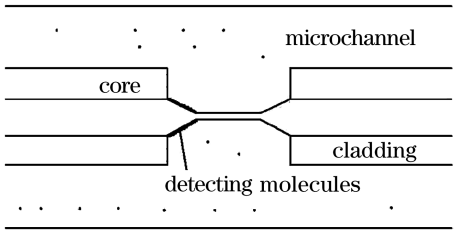

Fig. 1. Profile of fiber optic biosensor.

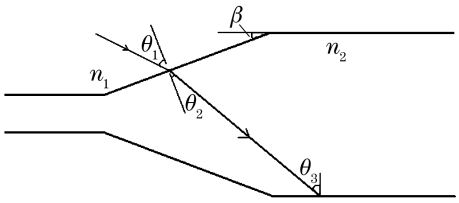

Fig. 2. Profile of part of receiving fluorescence.

cone surface and the tapered angle is β, where β is an angle between the inclined plane and horizontal direction. If $\beta > 90°$, the receiving fluorescent surface is a concave cone one; if $\beta = 90°$, the receiving fluorescent surface is a plane; if $\beta < 90°$, the receiving fluorescent surface is a convex cone surface. For total reflection in the optic fiber, if fluorescence received by the optic fiber can be transmitted far away, the incident angle must be greater than or equal to the critical angle; if the incident angle is less than the critical angle, the receiving fluorescent signal will lose. And that big or small of the incident angle depends on the incident angle of receiving cone surface in the optic fiber.

The receiving fluorescent part is indicated in Fig. 2. As fluorescence does not lose and can be transmitted a long distance in the optic fiber, the incident angle must be greater than or equal to the critical angle θ_3 for total reflection. n_1 and n_2 denote respectively relative refractive index of the optic fiber core for detecting solution and cladding. The relation can be get from the law of refraction:

$$\frac{\sin\theta_1}{\sin\theta_2} = n_1. \tag{1}$$

If the received fluorescence is totally reflected, we can get

$$\sin\theta_3 = \frac{1}{n_2}. \tag{2}$$

Considering the geometric relation in Fig. 2, we can obtain

$$\sin(\beta + \theta_2) = \sin\theta_3. \tag{3}$$

By Eqs. (1)—(3), we can get

$$F(\theta_2, \beta) = \sin\beta\cos\theta_2 + \cos\beta\sin\theta_2 - \frac{1}{n_2}. \tag{4}$$

Using KKT condition and Eq. (4), we can get

$$\frac{\partial F}{\partial \beta} = \cos\beta\cos\theta_2 - \sin\beta\sin\theta_2 = 0. \tag{5}$$

From Eqs. (1) and (5), we can derive the relation between the minimum incident angle θ_1 and the optic fiber tapered angle β:

$$\cot\beta = \left(\frac{n_1^2}{n_1^2 - \sin^2\theta_1} - 1\right)^{\frac{1}{2}}. \tag{6}$$

When $n_1 = 1.17$, $\beta, \theta_1 \in [0, \pi/2]$, the relation between cotangent of the optic fiber tapered angle and sine of the receiving fluorescent angle is presented in Fig. 3.

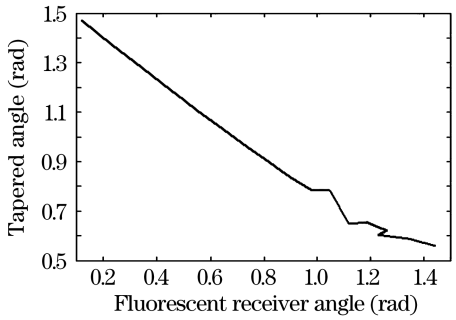

Fig. 3. Relationship between θ_1 and β.

Every dot of curves indicates all the relation between θ_1 and β and the value between θ_1 and β is one-to-one correspondence. In Eq. (6), if β is fixed, θ_1 can be obtained. The relation of Eq. (6) decides how much fiber optic biosensors can receive fluorescence and can directly affect the sensitivity of fiber optic biosensors. When $\beta, \theta_1 \in [0, \pi/2]$, if θ_1 increases, β decreases. When the receiving fluorescent surface is a concave cone surface, β increases with the increase of θ_1.

The static sensitivity of fiber optic biosensors plays an important role in sensor application, which is an important guideline. In Fig. 1, if the input signal of fiber optic biosensors is $x(I,t)$, the output signal y is $y(I,t)$, where the intensity I is the function of wavelength λ, which is $I = I(\lambda)$, differential equation for the zero-order system of fiber optic biosensors is

$$a_0 y = b_0 x, \tag{7}$$

$$\frac{y}{x} = \frac{b_0}{a_0} = s_0. \tag{8}$$

Transfer function for the zero-order system of fiber optic biosensors is

$$\frac{y(s)}{x(s)} = \frac{b_0}{a_0} = s_0, \tag{9}$$

where s_0 is static sensitivity of fiber optic biosensors.

From the construction of the fiber optic biosensors in Fig. 1, we can know that if the input light intensity I is the function of wavelength λ, the input and output signal can be denoted as $x(I,t) = I_E(\lambda_1)T(t)$, $y(I,t) = I_F(\lambda_2)\psi(\theta_1)T(t)$, respectively, where I_E and I_F are functions of input and output light intensity, λ_1 and λ_2 are the input and output light wavelength, $\psi(\theta_1)$ denotes the receiving proportion of $I_F(\lambda_2)$, which is also the function of θ_1, $T(t)$ is one order function of time.

Static sensitivity can be denoted as

$$s_0(\lambda_1, \lambda_2, \theta_1) = \frac{y(I,t)}{x(I,t)} = \frac{I_F(\lambda_2)\psi(\theta_1)T(t)}{I_E(\lambda_1)T(t)}. \tag{10}$$

Because the response time of the input and output light is very short, Eq. (10) can be written as

$$s_0(\lambda_1, \lambda_2, \theta_1) = \frac{I_F(\lambda_2)\psi(\theta_1)}{I_E(\lambda_1)}. \tag{11}$$

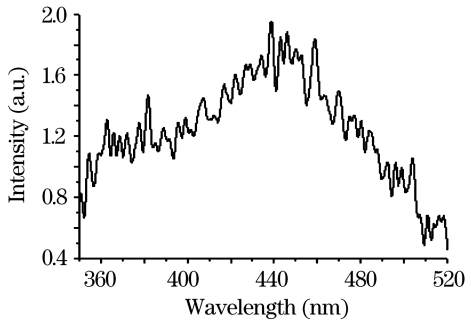

Fig. 4. Fluorescent curve of ZnSe solution (pH=8).

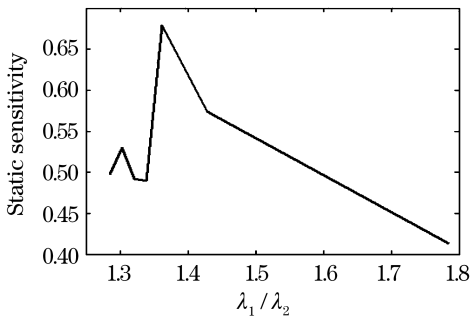

Fig. 5. Relationship between static sensitivity s_0 and λ_1/λ_2.

Table 1. Fluorescence Data from Fig. 4

Wavelength (nm)	360	365	370	375
Intensity (a.u.)	1.07413	1.14511	1.06216	1.05783
Wavelength (nm)	381.5	400	500	
Intensity (a.u.)	1.46731	1.23903	0.89278	

ZnSe nano-crystalline cluster is used as fluorescence marking molecules to study static sensitivity of fiber optic biosensors[11]. When $\lambda_1 = 280$ nm and $I_E(\lambda_1) = 2.16$, the fluorescent curve of ZnSe is shown in Fig. 4.

In Fig. 4, $I_F(\lambda_2)$ can be read from fluorescent curves of ZnSe. If β is known, θ_1 can be computed and $\psi(\theta_1)$ can be confirmed. Thus, the static sensitivity of fiber optic biosensors can be written as

$$s_0(\lambda_1, \lambda_2, \theta_1) = \frac{I_F(\lambda_2)\psi(\theta_1)}{I_E(\lambda_1)} = k\frac{1}{I_E(\lambda_1)}, \qquad (12)$$

where k is a constant. Data in Table 1 can be obtained from Fig. 4.

The static sensitivity of fiber optic biosensors s_0 can be drawn as the curve in Fig. 5. From the above analysis, if ZnSe nano-crystalline cluster is used for fluorescent marking molecules, the relation of the static sensitivity and the wavelength of fiber optic biosensors can be computed easily.

Construction of a novel fiber optic biosensor is simple, but it has some difficulties to solve, such as the size is too small to be processed. With the development of microprocessing technology, some submicron and nanometer structural device can be realized. Multimode optical fiber can be manufactured with microelectronics technology. Some small size protecting layer is added in the cone surface of the optic fiber, and then scraggy cone surface can be realized by etching technology. Laser processing technology is also used for ablating the optic fiber surface. The size of tapered angle of the receiving fluorescence can be etched by adjusting etching time in chemical etching solution.

In conclusion, the novel structure of fiber optic biosensors is introduced and analyzed. The relation between the optic fiber tapered angle and the fluorescence incident angle in signal receiving part is calculated. Besides, under the condition of the zero-order system, formula of the static sensitivity of fiber optic biosensors is computed. When ZnSe nano crystalline cluster is used for marking molecules, the static sensitivity of optic biosensors is simplified and calculated. Fiber optic biosensors as construction of Fig. 1 can be applied in microanalysis of microbe[12,13]. Combining microchannels processing technology and sensor technology can solve problems which other fiber optic biosensors cannot solve, for instance, studying single molecule fluorescent detecting, cutting down sample consumption, especially, and detecting molecules in blood[14].

This work was supported by the National Natural Science Foundation of China (No. 50735031, 60666001), Innovation Foundation of Guizhou University (No. 2007007), and the Natural Science Foundation of Guizhou Province (No. QKHJ[2007]2201). Z. Bai's e-mail address is yufengvc@163.com.

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