Sensors and Actuators B 199 (2014) 70–75

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Modeling and simulation of tapered fiber-optic oil concentration sensor using negative dielectrophoresis

Sheng Hu[a], Yong Zhao[b,*], Haifeng Hu[a]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[b] State Key Laboratory of Synthetical Automation for Process Industries, Shenyang 110819, China

ARTICLE INFO

Article history:
Received 26 January 2014
Received in revised form 13 March 2014
Accepted 16 March 2014
Available online 1 April 2014

Keywords:
Concentration sensor
Oil–water measurement
Dielectrophoresis
Tapered fiber
COMSOL simulation

ABSTRACT

This work presented the model of dieletrophoresis (DEP) and tapered fiber technology. The aim was to improve the sensitivity of oil concentration measurement in the separation of oil–water mixture process. Simulations via COMSOL v4.3b Multiphysics software were implemented to calculate and study the distribution of electric field, which was generated from both sides of tapered fiber with two metal-coated silver electrodes using direct current (DC) electric fields. The emulsified oil particles with radius of 0.09 μm could be repelled from the strong electric field region so as to change the refractive index around the tapered fiber region. Then, the evanescent wave field would induce to change the transmission intensity of the optical fiber. The finite element method (FEM) was used to solve optical wave field coupled convection–diffusion–migration (CDM) equation. The results indicated that the oil concentration measurement sensitivity of the proposed sensor was increased to be 25% higher than that of an identical tapered fiber sensor without negative DEP.

1. Introduction

In recent years, the separation of the oil–water mixture has become a research focus in the serious freshwater resources reduction. The treatment of domestic sewage and industrial effluent are based on the oil–water separation technology such as gravitational separation, centrifugal separation, electrolysis and biological methods [1] to address the growing problems of freshwater. Therefore, it seems to be particularly necessary to monitor the oil content in this process [2]. The low content of micro/nano oil droplet put forward the new challenge to traditional measurement. The dissolved oil, lubricant, disperse oil and float oil exist in the oil–water mixture. Especially, the emulsified oil droplets, whose size is below 10 μm, form a kind of tiny and stable drops in the water [3]. Optical fiber has a great of advantages for many sensing application, including high elastic strain limits, high sensitivity, electromagnetic interference resistance and low cost [4]. However, evanescent field fiber sensor which is also new and popular in the fiber sensor family processes higher sensitivity and deeper penetration than common optical fiber at present.

In addition, the DEP technology is widely used for cellular manipulation [5], liquid movement [6], semiconductor processing [7] and nanorod sensor [8]. Some researchers triumphantly put this technology applied in the sensing fields on later. Dan et al. [9] had immobilized the nanorods which contain poly-3,4-ethylenedioxythiophene/polystyrenesulfonate materials by DEP force. This device was utilized for concentration measurement of acetone, methanol and ethanol by a resistance change in electronic nose vapor sensing systems. Holzkia et al. [10] proposed a fiber-optical evanescent field sensor which depended on the positive DEP force to increase the content of water in order to improve the sensitivity in the lubricating oils.

Thus, this paper design and simulate an emulsified oil concentration sensor which combine the advantage of dielectrophoresis and tapered fiber technology. For this work, an obvious extension of this DEP technology is to introduce the repelling emulsified oils directly into a high sensing by the external non-uniform electric fields. The structure of tapered fiber has so fast time responses with changing refraction index of the medium. However, when the size of oil droplet became much smaller as the continuous purification of oil, the measurement in separation of oil–water is relatively difficult because its content might become low. The oil particles on the surface of the tapered fiber are distracted by the negative DEP. As a consequence, the refractive index of the tapered fiber surface result in the most light obeying the total reflection transmission.

---

* Corresponding author. Tel.: +86 13998812362.
E-mail addresses: zhaoyong@tsinghua.org.cn, zhaoyong@ise.neu.edu.cn (Y. Zhao).

http://dx.doi.org/10.1016/j.snb.2014.03.066
0925-4005/

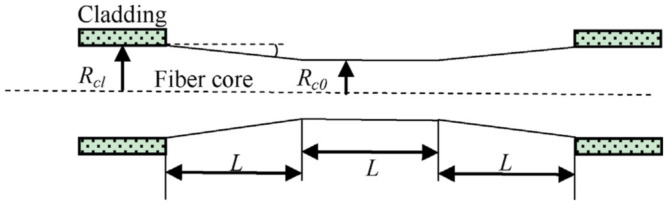

Fig. 1. The structure of linear tapered fiber.

Eventually the detection is achieved by the intensity factor ratio of the output light and the input light. The distribution of electric field can be calculated near the electrode. The geometry of the sensor is incorporated in a model that solve the optical wave equations within a tapered fiber with metal-coated film. The output light intensity of light source depends on oil concentration distributions have also been explored. It is expected that the results of this study would provide guidelines to achieve measurement of low content of oil via negative DEP.

2. Theoretical background and sensing model

2.1. Fiber evanescent field

The tapered fiber uses unclad uniform plastic fiber as its material, produce through heating and tapering. Three types of taper geometries are used, including linear, parabolic and exponential. They can change the distribution of longitudinal refractive index and form evanescent field in the cone zone as shown in Fig. 1. Compared with the latter two, linear tapered fiber is usually made and used [11,12]. This paper studies the oil–water simulation based on linear tapered fiber. On the optical fiber taper angle, some of the light that spread in optical fiber core would divulge to the outside of the fiber, because the refractive index of fiber core and surrounding solution is different. Thus, the light energy in-fiber could be reduced.

In evanescent field, the difference of the medium refractive index directly affect the penetration depth and energy of the evanescent wave. The intensity of transmission light in fiber core is changed. Evanescent wave penetration depth d_p is expressed as [11],

$$d_p = \frac{\lambda}{2\pi \cdot n_{co}} \frac{1}{\sqrt{\sin^2 \ \theta_i - (n_{cl}/n_{co})^2}} \tag{1}$$

where θ_i is the incident angle measured from the normal at the interface of core and surround, n_{co} is the refractive index of core, n_{cl} is the refractive index of cladding represented by the analytic solvent, λ is the vacuum wavelength of the guided light. The magnitude of evanescent field of fiber depends on the effect of incident angle, taper ratio (TR), taper length, light model number and numerical aperture. Fig. 1 shows the theoretical model, the TR is equal to R_{cl}/R_{co}, where R_{cl} and R_{co} is, respectively, the radius of the fiber core at the input and output ends of the taper. The taper angle is given as Eq. (2).

$$\varOmega = \tan^{-1}\left[\frac{R_{co} - R_{cl}}{L}\right] \tag{2}$$

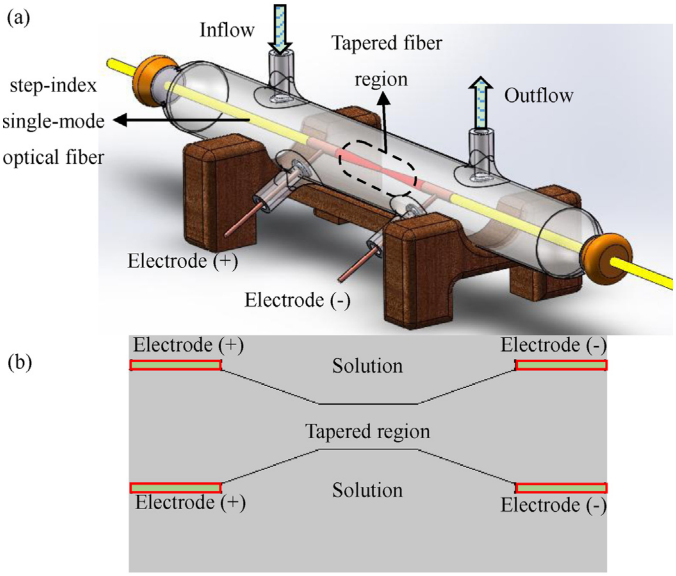

Fig. 2. (a) Sensor setup of emulsified particle concentration. (b) 2-D simplified domain of computation.

2.2. DEP force

If a non-uniform field can be produced by metal electrodes, some of neutral particles would find themselves in a field gradient. In this case, there are a net electrostrictive force acting on the particles, and they move relative to their surroundings. The motion of the particle would experience a mechanical force, which is also called as the DEP force [5], and its mathematical formula can be expressed as:

$$\left\langle \vec{F}_{eDEP} \right\rangle = 2\pi r^3 \varepsilon_m \alpha \left\langle \vec{E}_{rms} \right\rangle \tag{3}$$

where r is the radius of the particle, ε_m is the permittivity of the surrounding medium, $\vec{E}_{\text{rms}}$ is the root mean square of the electric field. The factor α which is traditionally described by the Clausius–Mossotti (CM) factor determined the particle polarization. The factor α is positive or negative value. Positive α value due to larger particle permittivity yield positive DEP force and particle movement toward high field density regions; negative α value yield particle motion down the field gradient [13]. When the frequency is zero, the factor α only depends on the conductivity of the medium and particles. Therefore, DC dielectrophoresis is differ from AC dielectrophoresis in relation to the CM factor α in Eq. (4), where σ stands for the conductivities of the particle (p) and the medium (m). The DC dielectrophoresis also reduce the external power requirements because of neglecting the effect of frequency component.

$$\alpha = \frac{\sigma_p - \sigma_m}{\sigma_p + 2\sigma_m} \tag{4}$$

2.3. Theoretic model

Based on the above description, a tapered fiber could be applied to liquid concentration detection because it have the high sensitivity. For continuous purifying oil, however, a great deal of filtrating and monitoring process can meet the requirement of drinking and living water. The proposed metal-coated electrodes are used to manipulate the particles of emulsion by means of a desired DEP effect. The sensor differs from surface plasmon resonance, which is the collective oscillation of electrons in a solid or liquid stimulated by incident light. With external applied electric filed, the metal-coated silver can generate the non-uniform electric fields to change the distribution of particles.

The distribution of refractive index around tapered fiber surface could be changed. Meanwhile, light intensify of the output is obtained in this way. Coating silver thin film, the linear tapered fiber which is ordinary step-index single-mode optical fiber is less expensive than the sapphire fiber. The theoretic model is shown in Fig. 2(a). The silver layer with 750 nm thickness can be loaded 10 V