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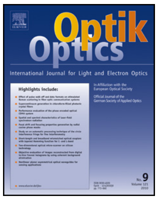

Measurement of the optical absorption coefficient for liquid based on optical microfiber

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ABSTRACT

An inline measuring method of the optical absorption coefficient for liquid based on optical microfiber (OM) is studied. If an OM is immersed into absorptive liquid, the additional loss of the OM will increase. We have analyzed the relationship between the additional loss of the OMs and the absorption coefficients of the liquids, and found that the OM with determinate construction will be useful for measuring the absorption coefficients of the liquid whose refractive index is lower than that of the OM. Two OM samples are prepared to measure the absorption coefficient of pure water. A supercontinuum source is launched into the OM sample which is immersed into pure water, and absorption spectrum from 1400 to 1700 nm has been achieved by monitoring the additional loss. The trend of the absorption spectrum is similar with that of the reported result, showing that the inline measurement of the optical absorption coefficient is a feasible method for those lower refractive index liquids.

1. Introduction

The optical absorption coefficient of liquid is a remarkable parameter in chemical, biological, atmospheric science and remote sensing fields. Conventional optical spectroscopic [1–3] and photoacoustic [4] techniques have been widely used to study the absorption property of various liquids, such as water, benzene, toluene, chlorobenzene, dichloromethane and so on. Owing to the special optical properties, including large evanescent field, strong optical confinement, high nonlinearity and convenient connectivity to other fiberized components [5–9], in the past several years, optical microfiber (OM) has attracted a lot interests and has been studied in many fields including current sensing, humidity sensing, and signal processing [10–14].

In the sensing field, OMs have the instinct advantage since a considerable fraction of the propagating optical power is out of the physical boundary of the OM profile. Based on the property, an inline absorption sensor with coiled OM was proposed and realized [15]. The absorption sensor consisting of an OM coil resonator embedded in fluidic channel walls was fabricated and tested. In additional, OM loops were theoretically investigated to use in refractive index and salinity sensing of seawater [16]. In this paper, we propose an easy and inline method to obtain the optical absorption spectrum of liquid just by immersing the sensing OM into the measured liquid and measuring the loss spectrum. When an OM is immersed into the absorptive liquids, the evanescent field interacts with the measured medium effectively, leading to an additional loss of the transmitted power. The relationship between the additional loss of the sensing OM and optical absorption coefficient of the tested liquid with lower refractive index than that of OM is analyzed in detail, different diameters and constructions of the sensing OM is considered. Then, a corresponding experiment has been set up, and the experimental results demonstrated the validity of the method to measure absorption coefficient of liquid.

Due to the small size of OM, the measurement can test the absorption coefficient of a little dose of liquid by direct intervention to the measured liquid. What's more, if we design OMs with different diameter and waist length to measure the absorption coefficient of the liquid, potentially wide sensing range for the absorption coefficient will be easily realized. For the liquid with large absorption coefficient, OMs with bigger diameter and shorter waist length can be chosen to reduce the loss of power.

2. Theory

When a sensing OM is immersed into the measured liquid, the evanescent field out of the OM will be disturbed and the total transmitting power through the OM will be attenuated due to absorption of the measured liquid, and the waveguide scattering caused by the roughness of the OM profile is ignored. To get the absorption coefficient of the measured liquid by just monitoring the additional loss, we should analyze the relationship between them firstly. But the relationship between them is not that easy as it likes.

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The refractive index of the OM is a real number, while, that of the surrounding liquid is a complex number. We can get the complex propagation constant by solving eigenvalue equations of the OM-liquid waveguide in complex number field. In mathematics, the absorption process can be ascribed to the imaginary part of the propagation constant. In practical, the absorption coefficient (α) of the measured liquids is usually small, so the influence of absorption of the measured liquids can be described as tiny perturbation to the waveguide without absorption. Based on the approximation, the relationship between the optical absorption coefficient of the measured liquid and the additional loss of the sensing OM will be calculated in detail. Since the additional loss of conical region and waist region of the sensing OM are different [17], we analyze them separately.

2.1. Waist region

When the waist of the sensing OM is immersed into liquid with lower refractive index, the liquid can be treated as an infinite cladding. Then, an optical waveguide is composed with the OM and the surrounding liquid, becoming a step-index profile.

The single-mode propagating condition of a step-index waveguide can be described with normalized frequency$v = 2\pi a\sqrt{n_1^1 - n_2^2}/\lambda$£2.405, where a is the radius of the OM, n_1 and n_2 are the real part of the refractive indices for the OM and the cladding, and λ is the light wavelength in vacuum. If the OM (n_1=1.45) is immersed into a kind of liquid (n_2=1.33), λ=1.55 μm, a must be less than 1 μm to ensure single-mode condition. If the diameter of the OM is given, the critical optical wavelength can also be calculated.

Assuming the measured liquid has no absorption firstly, the propagation constant is a real number under that condition, which is labeled asβ_1. And it can be solved from the corresponding eigenvalue equation by using the refractive index of the sensing OM and real part of the refractive index of the measured liquid.

If considering the absorption of the measured liquids, the complex propagation constant of the waveguide (β) would be [18]:

$$\beta = \beta_1 + j\beta_2 = \beta_1 + jk\eta_p\delta n = \beta_1 + j\eta_p\alpha/2, \tag{1}$$

Where k is the wave number in vacuum, η_p is the percentage of the power transmitted in the cladding, and $\delta n = \frac{\alpha\lambda}{4\pi}$ is the imaginary part of the refractive index of the measured liquid, $\alpha$is the absorption coefficient of the measured liquid, and$\beta_2 = \eta_p\alpha/2$is the imaginary part ofβ.

For an OM surrounded with low refractive index liquid, the average energy in the OM flows in the radial and azimuthal directions are zero, only the energy in z-direction is considered. In cylinder coordinate, the z-components of Poynting vectors S_{z1} (inside the core), S_{z2} (outside the core) are obtained as reference 19, shown as following,

$$S_{=1} = \frac{1}{2}\left(\frac{\varepsilon_0}{\mu_0}\right)^2 \frac{kn_1^2}{\beta_1 J_1^2(U)}\left[a1a3J_0^2\left(\frac{Ur}{a}\right) + a_2a_4J_2^2\left(\frac{Ur}{a}\right) + \frac{1-F_1F_2}{2}J_0\left(\frac{Ur}{a}\right)J_2\left(\frac{Ur}{a}\right)\cos(2\phi)\right], \quad (0 < r < a) \tag{2}$$

$$S_{z2} = \frac{1}{2}(\frac{\varepsilon_0}{\mu_0})^2 \frac{kn_1^2}{\beta_1 K_1^2(W)}\frac{U^2}{W^2}[a_1a_5K_0^2(\frac{Wr}{a}) + a_2a_6K_2^2(\frac{Wr}{a}) - \frac{1-2\Delta-F_1F_2}{2}K_0(\frac{Wr}{a})K_2(\frac{Wr}{a})\cos(2\phi)], \quad (r > a) \tag{3}$$

where$J_\upsilon(\upsilon = 0, 1, 2)$is the Bessel function of the first kind, and $K_\upsilon(\upsilon = 0, 1, 2)$is the Bessel function of the second kind, $\varepsilon_0$is electric medium constant,$\mu_0$is magnetic medium constant,

$U = a\sqrt{k^2n_1^2 - \beta_1^2}$,$W = a\sqrt{\beta_1^2 - k^2n_2^2}$,$\Delta = \frac{n_1^2-n_2^2}{2n_1}$

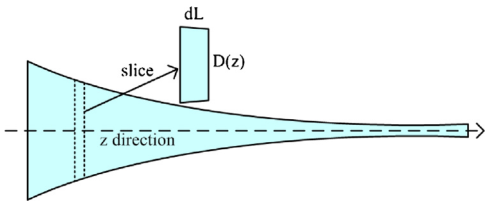

Figure 1. Schematic illustration of part of the conical region.

$a_1 = \frac{F_2-1}{2}$,$a_3 = \frac{F_1-1}{2}$,$a_5 = \frac{F_1-1+2\Delta}{2}$,$a_2 = \frac{F_2+1}{2}$,$a_4 = \frac{F_1+1}{2}$,$a_6 = \frac{F_1+1+2\Delta}{2}$,

$F_1 = (\frac{UW}{V})^2[b_1 + (1-2\Delta)b_2]$, $F_2 = (\frac{UW}{V})^2\frac{1}{b_1+b_2}$,

$b_1 = \frac{1}{2U}[\frac{J_0(U)}{J_1(U)} - \frac{J_2(U)}{J_1(U)}]$, $b_2 = -\frac{1}{2W}[\frac{K_0(W)}{K_1(W)} + \frac{K_2(W)}{K_1(W)}]$,

From the integral of the distribution of the Poynting vectors in z direction in the area of cladding, the fraction of the power propagated in the measured liquids η_p can be calculated as follow,

$$\eta_p = \frac{\int_a^\infty S_{z2}dA}{\int_0^a S_{z1}dA + \int_a^\infty S_{z2}dA}, \tag{4}$$

The propagated power$P$is linear with$\left|e^{j\beta z}\right|^2$, where z is the position along the transmitted direction. Therefore, if light is transmitted in the OM immersed into the measured liquid after a length of L, the additional loss (LL_w) will be got as follow,

$$LL_w = -10lg(\left|e^{j\beta L}\right|^2) \tag{5}$$

According to equation (1), the equation (5) can be simplified to be$LL_w = 10\alpha\eta_p lg(e)$, so we can get the absorption coefficient of the measured liquid by monitoring the additional loss.

2.2. Conical region

The equation (5) is deduced based on the uniform diameter, but actually, the sensing OM is fabricated by heating and drawing the conventional SMF, which have a uniform waist and two conical regions [17]. When the sensing OM is immersed into the measured liquid, the additional loss caused by the conical region is relative to the size of the cross section.

As shown in Figure 1, the cross section at different z position in the conical region has different diameter. To calculate the additional loss for the conical region, we can divide the conical region into a series of small slices, and each slice has diameter D(z) and length dL (D(z) can be calculated according to reference 17). The additional loss of the slice$ll_s(z)$can be obtained according to equation (5), and the total loss of the conical region(LL_c)is the accumulation of the additional loss of all the slices, shown as follow,

$$LL_c = \int_{l_c} ll_c(z), \tag{6}$$

where$l_c$is the length of the conical region. It should be pointed out that the number of the divided slices can be properly selected according to the calculation precision.

For a sensing OM with determinate construction, we can get the one-to-one correspondence between the absorption coefficient of measured liquid and the additional loss of sensing OM according to equation (5) and (6). So, measurement of the absorption coefficient based on OM can be realized by just monitoring the additional loss of the determinate sensing OM.

2.3. Simulation results

When the sensing OM is totally immersed into the measured liquid, the additional loss is relative to the construction of the sensing