An Inline Airborne Molecular Contaminants Sensor Based on Optical Microfiber

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Abstract. The rudimental airborne molecular contaminants (AMCs) will obviously reduce the lifetime of the lens widely used in the high peak power laser system. An inline AMCs sensor based on the optical microfiber (OM) is here proposed. When the AMCs adhere on the profile of sensing OM, the covering film would disturb the evanescent field transmitted out of the OM, and an additional loss would occur due to the absorptive attribution of the AMCs. The relationship between the thickness of the covering film and the additional loss is numerically calculated.

Introduction

Inertial confinement fusion (ICF) is a type of fusion energy research, and energy is delivered to the outer layer of the target using high-energy beams of laser light. Vacuum technique is widely used in the field of high peak power laser system[1–3], space technology, materials technology, and so on. Airborne molecular contaminants (AMCs), which are harmful to system, are produced by slow outgassing of residues of high molecular weight compounds. For example, AMCs are known to seriously degrade the performance of sol-gel coated optics which has been widely used as the optical components in high peak power laser systems for their excellent optical properties and high laser-induced damage thresholds[4–6]. But, it is hard to monitoring the AMCs inline.

To solve the problem mentioned, we propose a new method for AMCs monitoring based on optical microfiber (OM). OM has recently attracted much attention because of the enormous progress in the fabrication of low-loss structures which allow for low-loss evanescent waveguide[7,8]. When the light is transmitted in the OM, it is tightly confined to the core for the large refractive index contrast between core and air, while a relative large fraction of the guided power propagate out of the physical boundary as evanescent field, which makes it highly sensitive to the tested medium. For the excellent properties, OM is widely used in the sensing field[9-11].

Modeling of OM Covered By Film

Once the AMCs adhered symmetrically to the profile of the sensing OM which is fabricated from the conventional optical fiber, a film covers the surface of the OM, the light transmitted through the OM will be disturbed and part of the energy will propagate in the newly formed film. If the AMCs film has an absorption coefficient at the guided wavelength, an additional loss will increase, which is related to the thickness, the refractive index and the absorption coefficient of the film. Therefore, the thickness of the determinate AMCs film can be estimated through monitoring the additional loss.

For basic consideration, we assume the waist region of the sensing OM has a circular cross-section, an infinite clad, and a step-index profile. To be simple, only fundamental mode is calculated, and the conical region should satisfy the adiabatic criterion to avoid mode converting[12]. For the optical
fiber used in the experiments, $n_1=1.451$ (the refractive index of OM), $n_2=1$ (the refractive index of air), if $\lambda=1.55\mu$m, the diameter must be less than $1.1\mu$m to ensure single mode[13].

When AMCs film adheres to the surface of the sensing OM, part of the power will be transmitted in the film, so the additional loss will increase owing to the absorptive attribution of the film. In mathematics, the absorption progress can be ascribed to the imaginary part of the propagation constant ($\beta$). As we know, the complex amplitude of the electric field propagating in the optical fiber waveguide is linear with $e^{i\beta z}$, where $z$ is the position along the propagation direction, and the power transmitted can be described as linear with $e^{2i\beta z}$. The imaginary part of the propagation constant induces the additional loss of the power, and the additional loss can be calculated as follow.

$$\text{Loss} = 10\log_{10} e^{-2\beta L} = -20\beta L \approx 8.686\beta L$$  \hspace{1cm} (1)

Where $\beta_i$ represents the imaginary part of the propagation constant, and $L$ is the transmitted length. But, it is difficult to directly solve $\beta$ according to eigenvalue equations[14] in complex number field. In this paper, 2D Finite Element Method (FEM) was used to numerically solve Maxwell equations and got the effective index of mode.

**Simulation Results**

The numerical model was defined, solved and analyzed using COMSOL 4.2 multiphysics. The modeling geometry is shown in Fig. 1(a). The refractive indices of core and air are 1.451 and 1, respectively. The sensing OM is covered by film, and surrounded by air. The chosen boundary condition was perfect matched layer (PML) at the outer surface. Assuming the refractive index of the film is 1.5, the absorption coefficient of the film is 10/cm, the thickness of the film is 100nm, the optical wavelength is 1.55\mu$m and the diameter of OM is 1.3\mu$m, Fig. 1(b) show the electric field distribution of the OM cross-section, and part of power is transmitted in the film, causing the additional loss. The propagation constant is $5.30 + i 4.64 \times 10^{-5} \mu \text{m}^{-1}$ (i is unit imaginary number), so the additional loss can be obtained as 0.403dB/mm according to Eq. 1.

![Figure 1](image)

Figure 1. (a) Schematic of the calculated model (b) the electric field of the OM cross section for the 1.3\mu$m diameter OM covered by AMCs film (the thickness of the film is 100nm).

Obviously, the additional loss caused by the covering film is different for conical region and waist region of the sensing OM. So, OM with different diameter was considered in the calculation. The parameters used in the simulation are listed as below. The refractive index of the film is 1.5 for 1.55\mu$m optical wavelength, the absorption coefficient of the film is 10/cm, the thickness of the film is 100nm, the diameter of the OM is 1.3\mu$m, relative rate of the hot-zone change and taper elongation ($\alpha$) is 0.2[15], and the length of the waist region is 4mm. As shown in Fig. 2(a), the profile of the sensing OM is calculated and plotted in solid line, and the corresponding additional loss caused by 100nm thickness film with different diameter along the OM is shown in dash line.
As discussed above, the additional loss caused by different part of OM is not the same, and the total loss caused by the covering film is the summation of the whole profile for the sensing OM[16]. For example, the total loss of the OM in Fig. 2 (waist diameter is 1.3µm, waist length is 4mm, the thickness of the film is 100nm, and α is 0.2) is integral of the dash area. By scanning the thickness of covering film ranging from 10nm to 300nm and changing the waist diameter of sensing OM, we obtain the corresponding total loss of OM, which is shown in Fig. 3. The thicker of the film is, the larger the total loss is. This may be useful for the determination of the thickness of the film covering the waist of the OM. Although the OM with the diameter of 1µm is more sensitive to the AMCs film than that of the 1.5µm one, the measuring range of the thickness of the film is much smaller. The AMCs sensor based on the OM has potentially wide sensing range for many kinds of absorptive AMCs by controlling the diameter and the waist length of the OM.

Figure 3. The total loss of OM with different waist diameter (the waist lengths are all 4mm, and α of the OM are all 0.2).

As the red line shown in Fig.3, the sensitivity of the AMCs sensor is about 0.025dB/nm. Once the material of the AMCs and the total loss caused by the AMCs film are known, we can get the thickness of the film according to Fig. 3 easily. If the background noise is 0.01dB of the power measurement system, sub-nm thickness of AMCs is measureable, which is high-precision.

Summary
In conclusion, an inline AMCs sensor based on OM is proposed and simulated. The AMCs sensor can perform inline, simple, high-precision, which is just fit the requirements of the high peak power laser system bothered by residual AMCs. In addition, the AMCs sensor can be tailored by controlling the construction of OM, and has potentially wide sensing range for many kinds of AMCs with an absorption coefficient. For the AMCs with large absorption coefficient, OMs with bigger diameter can be chosen to reduce the loss of power. Through controlling the diameter and the length of OM, which leads to the transformation of evanescent field, large AMCs measuring range can be obtained. Furthermore, it is easy to measure the AMCs inline and convenient to realize multiplexing.
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