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Regular Articles

A practical approach for optical characterization of a film coated on the optical fiber ☆,☆☆

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ABSTRACT

Phase Diffraction (PD)[1] which is a result of the interaction of light waves with a transparent object, is exploited to characterize precisely optical properties of dielectric films coated on the optical fiber without harming any feature of the sample. Typical fiber sensor applications require films coated on the side surface of the optical fiber and optical properties of that curved films are crucial for design purposes. In this study, three Polyvinyl Alcohol (PVA) films are prepared, their thicknesses are estimated based on the phase diffraction method by fitting experimental results with a mathematical model within 2.3% error. The outcomes of this practical method show good agreement with findings of the destructive Scanning Electron Microscopy (SEM) measurements. The method has the potential to allow real time monitoring abrupt changes of surrounding medium's properties and to examine coating quality (i.e. thickness uniformity) of the film.

1. Introduction

Optical films are widely used for modulating light in various scientific and practical applications, such as optoelectronics, integrated optics, semiconductor technologies, and especially for optical sensors. Thus, precise measurement of the film properties (i.e. thickness and refractive index) is essential to obtain better optical performance. It becomes challenging process in recent years due to nanometer scale of film thickness requirements which is comparable or shorter than wavelengths of visible light. Conventional optical methods to characterize optical properties of films are based on interferometric methods [1,2] and ellipsometric methods [3,4]. For the curved substrates as in [3], change of the polarization state is interrogated, it is a complicated procedure. Furthermore, laboratory environment requirement of aforementioned methods results in preventing effective engineering fabrication.

Diffraction of a plane wave from a phase object is very rich subject and brings wealth of application, since phase of the wave is more sensitive to refractive index change than the amplitude. Accordingly, the resultant phase diffraction pattern is contributed by the phase variation of transversing wave front through the curved film. Since the curved geometry globally modifies the wave front, features of the diffraction pattern (e.g. main lobe width) is the reflection of the film properties (e.g. quality, thickness). The approach is adapted for optical fiber based narrow dielectric films in this study.

Typical optical fiber sensor applications including surface plasmon resonances require dielectric polymer films (PVA etc.) coated on side surface of an optical fiber [5–7]. Therefore, nondestructive characterization of these films is crucial for designing, implementing, and monitoring such devices.

This letter presents the experimental results and estimations from a mathematical model of the diffraction of plane waves from a dielectric film coated on the optical fiber. When a light wave traverses the dielectric film, the particular regions of the wave front passing through peculiar sections of the film undergo specific phase delays as in Fig. 1. The region of the wave fronts passing through the phase object traced geometrically using optical ray approach [8] and more comprehensive studies have recently been done as well [9]. In [9], the intensity distribution of the light diffracted from phase steps of one and two dimensions in reflection and transmission modes are analyzed. A mathematical method based on Fresnel-Kirchhoff diffraction theory under paraxial approximation is exploited in this study. The diffraction pattern that is recorded by CCD camera is compared to results of the mathematical model to estimate thickness of the dielectric film coated on optical fiber provided that remaining parameters are known. The method can also be expanded for simultaneous estimation of

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☆☆ The second title footnote which is a longer than the first one and with an intention to fill in up more than one line while formatting.
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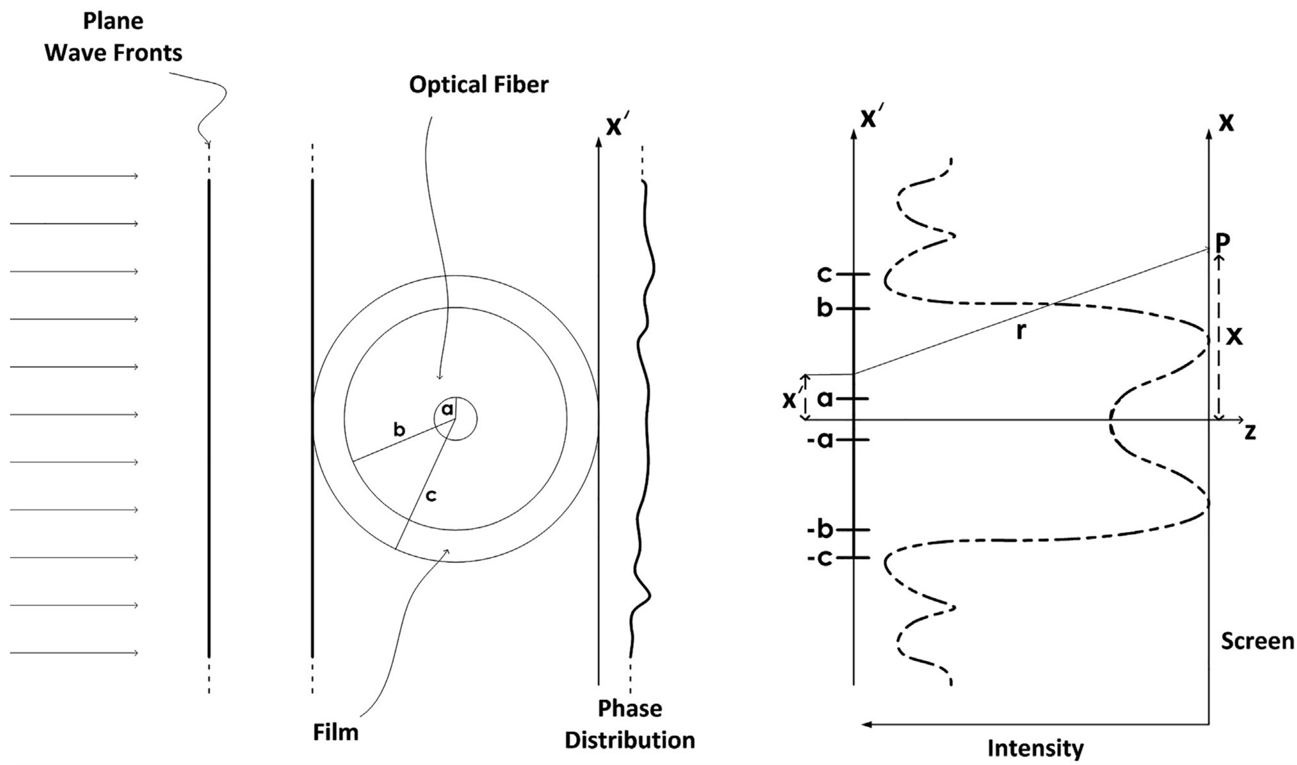

Fig. 1. Typical diffraction pattern of transmitted plane wave fronts through coated optical fiber and the diffraction geometry.

refractive index value of the film together with its thickness by using at least two different monochromatic light sources. Furthermore, this approach may be used for real time monitoring of changes in the surrounding medium properties (e.g. humidity level) which is the fundamental mechanism of many optical fiber sensor system.

Optical fibers are used as a cylindrical base in these works due to its perfect geometry, well defined optical properties, widespread usage, and easy accessibility. Apart from these, the method can easily be adapted for any kind of geometry that is transparent at the wavelength of interest. The approach was already applied for estimating the optical fiber core refractive index and its diameter [10] and adapted for a channel waveguide geometry which is laser direct-written in photopolymer substrates to characterize refractive index profile [11]. This letter propose a novel nondestructive practical approach for the curved dielectric films having their thicknesses comparable with the wavelength of interest and dimensions of the optical fiber.

2. Mathematical model

A mathematical model based on ray tracing and Fresnel-Kirchhoff diffraction integral is adapted for the problem under paraxial approximation [10,11]. It is assumed that there is no optical variation along the optical fiber axis. Therefore, the problem can be considered only in the cross-section plane. After the optical rays propagating through different parts of the coated optical fiber, the uniform wave front points advance and exhibit a phase distribution. This process can be modeled by using ray tracing between the entering plane and the exit surface of the film. Then, the resultant wave front experiences diffraction (self interferences) between the exit surface of the film and an observation plane as shown in Fig. 1.

Optical fibers are considered as two layer geometry in the previous study [10]. Here, the model is extended for coated optical fibers (three layer geometry) by using the similar approach. The amplitude of the diffracted wave on the observation plane at an arbitrary point P in Fig. 1:

$$\begin{aligned}U(P) =& K\{1 + C(\gamma) - C(\xi) + j[1 + S(\gamma) - S(\xi)]\\ &+\sqrt{\frac{2}{\lambda z}}\left(\int_{-c}^{-b} exp(-j\phi_p)exp\left[jk\frac{(x-x')^2}{2z}\right]dx'\right.\\ &+\int_{-b}^{-a} exp(-j(\phi_p+\phi_{cl}))exp\left[jk\frac{(x-x')^2}{2z}\right]dx'\\ &+\int_{-a}^{a} exp(-j(\phi_p+\phi_{cl}+\phi_{co}))exp\left[jk\frac{(x-x')^2}{2z}\right]dx'\\ &+\int_{a}^{b} exp(-j(\phi_p+\phi_{cl}))exp\left[jk\frac{(x-x')^2}{2z}\right]dx'\\ &\left.+\int_{b}^{c} exp(-j\phi_p)exp\left[jk\frac{(x-x')^2}{2z}\right]dx'\right)\Bigg\},\end{aligned} \tag{1}$$

in which a, b, and c are the core, the cladding, and the coated optical fiber radii. C and S are Fresnel cosine and sine functions. Their dependency on γ and ξ indicate $\sqrt{2/(\lambda z)}(x-c)$ and $\sqrt{2/(\lambda z)}(x+c)$, respectively. Finally K, ϕ_p, ϕ_{cl}, and ϕ_{co} are

$$\begin{aligned}&K = A\sqrt{\frac{-j}{2}}\exp(jkz)\exp(-j2kbn_s),\\ &\phi_p = 2k\sqrt{c^2-x'^2}(n_p-n_s),\\ &\phi_{cl} = 2k\sqrt{b^2-x'^2}(n_{cl}-n_p),\\ &\phi_{co} = 2k\sqrt{a^2-x'^2}(n_{co}-n_{cl}),\end{aligned} \tag{2}$$

where $A, n_s, n_p, n_{cl}, n_{co}$, and k are the amplitude of the disturbance, refractive indices of the surrounding medium, the coated material, the cladding, the core, and wave number, respectively. Light inten-