Journal of **Kim Il Sung** University Vol. 3 No. 3
(Natural Science) Juche103(2014)

Scattering Characteristics of Laser Light by Step-Index Fiber

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Abstract We investigated scattering characteristics of laser light of step-index fiber by numerical interpretation of Maxell equation.
Key words forward and backward scattering, refractive index profile

Introduction

The great leader Comrade **Kim Il Sung** said as follows.

"**Long-term research should be conducted with a view to opening up new scientific fields and introducing the latest developments in science and technology widely in the national economy.**"("**KIM IL SUNG** WORKS" Vol. 35 P. 313)

The refractive index profile of the optical fiber core plays an important role in characterizing the optical properties of the fiber. It allows determination of the fiber numerical aperture, the number of propagation modes within the fiber core and the dispersion of the fiber's material. Therefore, the detailed knowledge of the refractive index profile allows the prediction of the impulse response of the fiber and consequently the information carrying capacity of the fiber can be estimated.

The ideal measuring method should satisfy the following conditions: non destructive, applicable to any profile, high measurement accuracy, high resolution and easy measurement and data processing.

Different methods were used to determine the fiber's refractive index profile such as: near field method, X-ray microanalysis, scanning electron microscope and interferometric methods.

Many investigators have applied interferometric techniques to determine the optical properties of fibers [1－5].

A method capable of measuring both the refractive index and the diameter of optical fibers based on the analysis of the backscattered light, when a beam from a cw laser is incident perpendicular to the fiber axis, has been reported. But study results that put an comprehensive interpretation on forward and backward scattering distribution of light by step-index fiber not sufficient [6, 7].

The aim of the present work is to study the forward and backward scattering distribution of laser beam by the step-index profile of optical fibers.

1. Interpretation Model

In the cylindrical coordinate system (r, ϕ, z), scalar wave equation and its solution are as follows.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\psi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2}+\frac{\partial^2\psi}{\partial z^2}+k^2\psi=0 \tag{1}$$

$$\psi_n(r, \phi, z)=Z_n(\rho)e^{in\phi}e^{iihz} \quad (n=0, \pm 1, \cdots) \tag{2}$$

where $\rho=r\sqrt{k^2-h^2}$ and Zn is solution of Bessel equation.

$$\rho.\frac{d}{d\rho}\left(\rho\frac{d}{d\rho}z_n\right)+(\rho^2-n^2)=0 \tag{3}$$

Vector function that is generated by equation (2) is as follows.

$$\boldsymbol{M}_n=\nabla\times(\hat{e}_z\psi_n), \quad \boldsymbol{N_n}=\frac{\nabla\times\boldsymbol{M_n}}{k} \tag{4}$$

When a plane wave polarized along fiber axis is incident perpendicular to fiber axis, electric field vector of incident light and expansion of incident light field are as follows.

$$E_i=E_0\hat{e}_z e^{-jkr\cos\phi} \tag{5}$$

$$E_i=\sum_{n=-\infty}^{\infty}E_0(-1)^n\frac{\boldsymbol{N}_n}{k} \tag{6}$$

Phase of field has to equal in the z axis because plane wave is incident perpendicular to fiber axis. Thus in the equation (2) h is zero.

Expansion of scattering light field has to expressed as linear combination of vector functions. That is

$$\boldsymbol{E}_s=\sum_{n=-\infty}^{\infty}E_0(-1)^n/k(b_n\boldsymbol{N}_n+ia_n\boldsymbol{M}_n) \tag{7}$$

According to a boundary condition a_n is zero and b_n is as follows.

$$b_n=\frac{F_n(mkR_1)J_n'(mkR_1)-mF_n'(mkR_1)J_n(mkR)}{F_n(mkR_1)H_n^{(1)'}(mkR)-mF_n'(mkR_1)H_n^{(1)}(mkR)} \tag{8}$$

where m_1, R_1 are index and radius of core , m, R are index and radius of cladding. And F_n is expressed as

$$F_n(mkR_1)=\frac{\pi kR_1}{2}\{\alpha J_n(mkR_1)-\beta N_n(mkR_1)\} \tag{9}$$

where

$$\alpha=m_1J_{n+1}(m_1kR_1)N_n(mkR_1)-mJ_n(m_1kR_1)N_{n+1}(mkR_1)$$

$$\beta=m_1J_{n+1}(m_1kR_1)J_n(mkR_1)-mJ_n(m_1kR_1)J_{n+1}(mkR_1)$$

From equation (8) and (9) b_n is changed according to index of core m_1, optical radius of core m_1R_1 and optical radius of cladding mR, thus the information for indices and radiuses of core and cladding is included among the scattering light field.

At a long distance from cylindrical fiber scattered field is approximately as follows.

$$\boldsymbol{E_s} = -E_0 e^{2\pi/4}\sqrt{\frac{2}{\pi kr}}e^{ikr}\sum_{n=-\infty}^{\infty}[(-1)^n e^{in\phi} b_n \hat{e}_z] \tag{10}$$

The strength of light is proportional to square of the amplitude. that is

$$I_s \propto |E_S|^2 \tag{11}$$

2. Interpretation Results

The refractive indices of the core and the cladding and the difference between them and the diameter of the core are the basic parameters that specify the information transmission characteristics of the fiber.

Scattering light strength distributions for typical step-index fibers is shown in Fig. 1 ($a_1 = 45\mu$m, $a_2 = 90\mu$m, $m_1 = 1.5$, $m_2 =$ 1.60, 1.55, 1.50, 1.45, 1.40).

In Fig. 1, strength distributions of a), b) are the scattering light strength distributions of typical step-index fiber in case of $m_2 > m_1$, and d) and e) in case of $m_2 < m_1$. And c) corresponds to the scattering light strength distributions of single fiber in case of $m_2 = m_1$.

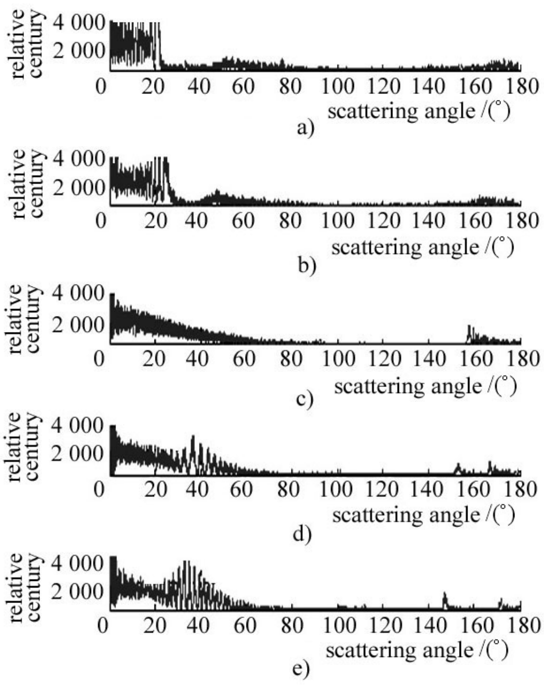

Fig. 1. Scattering light strength distributions for typical step-index fiber

$R_1 = 45\mu$m , $R = 90\mu$m , $m_1 = 1.5$ and a) m=1.6, b) m=1.55, c) m=1.5, d) m=1.45, e) m=1.4

As shown in Fig. 1, forward scattering light strength distributions in cases of $m_2 > m_1$ and $m_2 < m_1$ have modulated due to the presence of core but angle range of modulation and modulation form differs from each other. Forward scattering light strength distribution of single fiber has not modulated.

In case of $m_2 < m_1$, it is characterized to appear second maximum in the backward scattering light strength distribution besides first maximum that come into sight on backward scattering light strength distribution of single fiber.

Fig. 2 shows the scattering light strength distributions for optical fibers of $m_2 < m_1$.

As shown in Fig. 2 the larger the difference between indices of core and cladding, the more is number of modulation pattern in the forward scattering light strength distribution and the narrower is half width of modulation curve in the backward scattering light strength distribution the larger the difference between indices core and cladding, the larger the interval between first maximum and second maximum of the backward scatterin light strength distribution. The position of first maximum angle depends on only the index of cladding.

Fig. 3 shows the strength distributions of scattering interference pattern for fibers of $m < m_1$ in angle range of 35～50°.

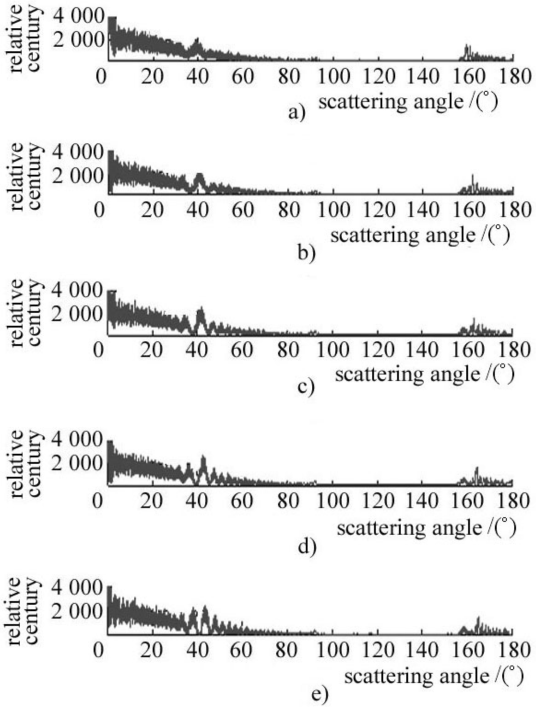

Fig. 2. Scattering light strength distributions for step-index fibers of $m_2 < m_1$

a)－e) are m_1 =1.505, 1.510, 1.515, 1.520 and 1.525 respectively

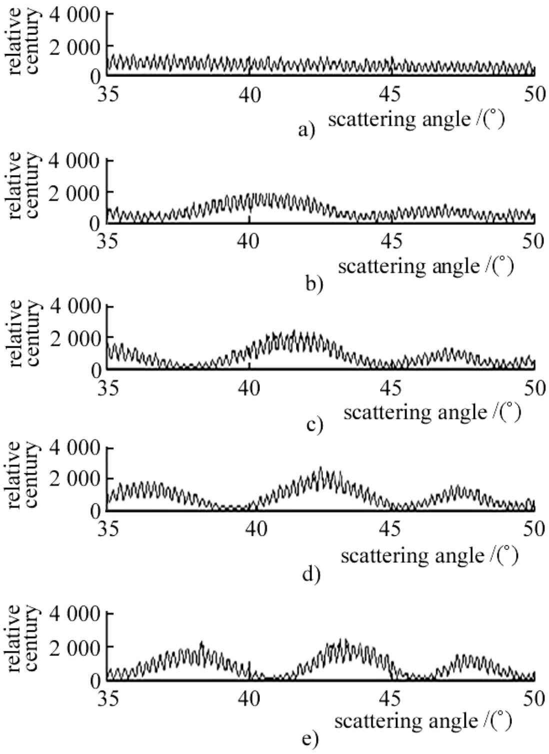

Fig. 3. Strength distributions of scattering interference pattern in 35－45° angle range

$m < m_1$, R= 90μm, R_1 = 45μm, m =1.5, λ=0.63μm.

a) m_1 =1.5, b) m_1 =1.51, c) m_1 =1.515, d) m_1 =1.52, e) m_1 = 1.525

From the Fig. 3 we can know that the index of core have an effect on modulation only and have no effect on the structure of scattering interference pattern.

Fig. 4 shows effect of core radius on the scattering light strength distribution.

As show in Fig. 4 the first minimum angle of modulation pattern depends strengthly on the radius of core.

For $m > m_1$ case, the scattering light strength distributions have shown Fig. 5.

As shown in Fig. 5, also for fibers of $m_2 > m_1$ the larger the difference between indices of core and cladding, the more is number of modulation pattern in the forward scattering light strength distribution and the narrower is half width of modulation curve. but it is characteristic that the maximum angle (or minimum angle) moves to low angles.

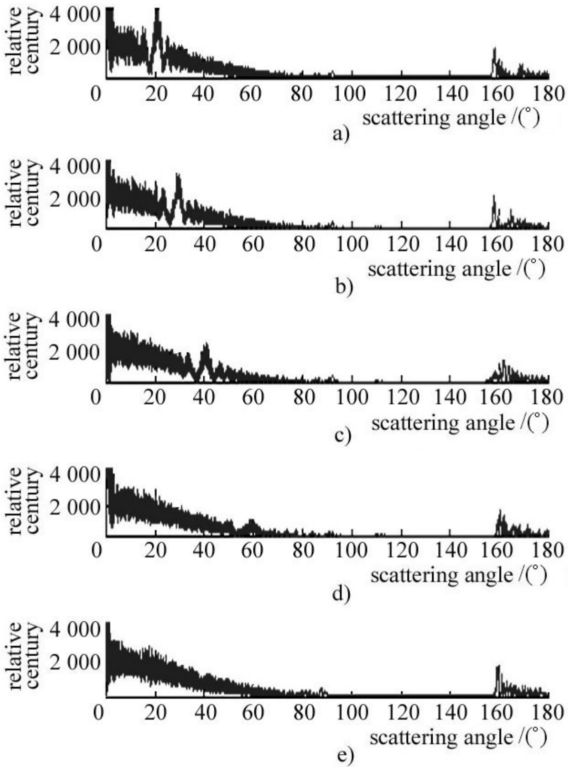

Fig. 4. Effect of core radius on the scattering light strength distribution

m_1 =1.51, a)－e) are the case of 0.3－0.7 of a_2

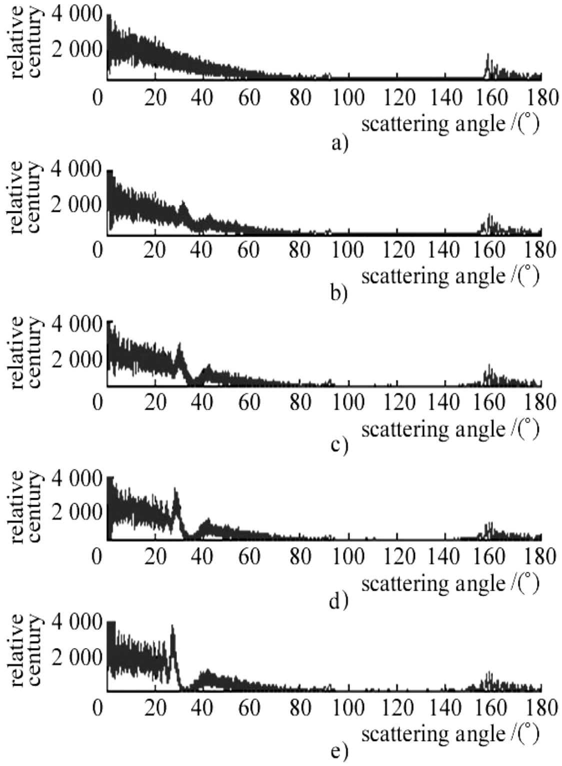

Fig. 5. Scattering light strength distributions for step-index fibers of $m_2 > m_1$

$a = 90\mu$m, $a_1 = 45\mu$m, $m = 1.5$, $\lambda = 0.63\mu$m,

a) $m_1 = 1.5$, b) $m_1 = 1.495$, c) $m_1 = 1.490$,

d) $m_1 = 1.485$, e) $m_1 = 1.48$

Conclusion

The forward scattering light strength distribution by step-index fiber is very sensitively changed according to the difference between indices of core and cladding. In the backward scattering light strength distribution the larger the difference between indices core and cladding, the larger the interval between first maximum and second maximum of the backward scattering light strength distribution. The position of first maximum angle depends on only the index of cladding. the backward scattering light strength distribution have modulated due to the presence of core different to index of cladding and thus and appeared the second maximum. The index of core have an effect on modulation only.

And the radius change of core of the step-index fiber give rise to the modulation of the forward scattering light strength distribution. The larger the difference between indices of core and cladding, the more is number of modulation pattern in the forward scattering light strength distribution and the narrower is half width of modulation curve.

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