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Measurement of the Refractive Index Profile of an Optical Fiber by Fresnel Diffraction

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Summary: In this work we present a non-destructive technique based on Fresnel diffraction to obtain the refractive index profile of a fiber grating. The system has been firstly calibrated by using the experimental data of the diffraction pattern of rectangular slits at different distances.

Keywords: Fiber gratings, Fresnel diffraction, Interferometry.

1. Introduction

There are different techniques to measure the profile of the refractive index in optical fibers [1-5]. For example by means of transverse interferometry [3], measurement of the deflection angle with axial illumination [4], scattering pattern with transverse illumination, etc. In this work, the values of the refraction indices of cladding and core will be obtained by means of a non-destructive method based on the application of the Fresnel integral, described in [5]. The optical fiber is treated as a 1-D phase object, which is illuminated perpendicularly to its axis by a parallel coherent beam of monochromatic light. Then measuring the normalized intensity distribution on the diffraction pattern of the fiber in the Fresnel regime, the refractive indexes of the fiber core and cladding are obtained from the latter by the last square technique. In this work, the measurement system will first be calibrated, first obtaining the Fresnel diffraction pattern of rectangular apertures at different distances and comparing the experimental and theoretical results. This method will allow obtaining the distance of the optical fiber to the CCD camera with enough precision. Subsequently, the theoretical curve of the Fresnel diffraction pattern will be adjusted to the experimental data obtained by illuminating the optical fiber.

1.1. Theoretical Model

We will start by considering that an object placed in the input plane is illuminated by a monochromatic wave. The field $U(P)$ at a point P (x,y) can be obtained from the field evaluated at the input plane U(x',y') (described with coordinates x', y'), by applying Fresnel approximation to Fresnel-Kirchhoff integral [6]:

$$U(P) = \frac{e^{ikz}}{i\lambda z} \iint_{-\infty}^{\infty} U(x',y') exp\left\{i\frac{k}{2z}[(x-x')^2 + (y-y')^2]\right\} dx'dy', \quad (1)$$

where λ is the wavelength of incident light, k is the wavenumber and z is the perpendicular distance between the input plane and the observation point P.

We will assume in this work that the integral (1) can be separated into the product of two one-dimensional integrals:

$$U(x,y) = \frac{e^{ikz}}{i} I_x(x) I_y(y). \quad (2)$$

It is important to notice that this is assumption has not general validity, but it is applicable to the two cases we are going to consider, namely an unit amplitude incident wave onto a rectangular aperture and an optical fiber. In fact is applicable whenever $U(x',y')$ can be separated into the product of two one-dimensional amplitudes, where

$$I_x(x) = \frac{1}{\sqrt{\lambda z}} \int_{-\infty}^{\infty} U(x')\, exp\left[i\frac{k}{2z}(x-x')^2\right] dx', \quad (3)$$

$$I_y(y) = \frac{1}{\sqrt{\lambda z}} \int_{-\infty}^{\infty} U(y')\, exp\left[i\frac{k}{2z}(y-y')^2\right] dy'. \quad (4)$$

The intensity of the field at point P(x,y) is computed by $I(x,y) = |U(x,y)|^2$.

Due to the independence of the last two integrals with respect to the other variable, one can concentrate in observing the diffraction pattern by varying either x or y coordinate. In our case, by absorbing the contribution of the y dependence in a constant K, the wavefield amplitude at point P can be finally expressed as:

$$U(x) = K e^{ikz} I_x(x). \quad (5)$$

We will now apply equation (5) to find the intensity distribution at distance z of an aperture and an optical fiber.

For the aperture, the amplitude at the input plane can be defined as:

$$U(x') = rect\left(\frac{x'}{2h}\right), \quad (6)$$

where h is in this case the width of the aperture. Substituting equation (6) in (3):

$$I_x(x) = \frac{1}{\sqrt{2}}\{[C(\beta) - C(\alpha)] + i[S(\beta) - S(\alpha)]\}, \quad (7)$$

where $C(\alpha)$ y $S(\alpha)$ are Fresnel integrals and

$$\alpha = -\sqrt{\frac{2}{\lambda z}}(h + x),$$

$$\beta = \sqrt{\frac{2}{\lambda z}}(h - x).$$

The final intensity distribution as a function of x is:

$$I(x) = K'^{\{[C(\beta)-C(\alpha)]^2+[S(\beta)-S(\alpha)]^2\}}, \quad (8)$$

where K' is a constant.

In order ro treat the diffraction of a fiber grating we will follow the calculations of reference [5], which are included here for completeness. We will assume that the phases accumulated by light from a plane just in front of the fiber and another just before the fiber are:

$$\varphi_{Su} = 2kbn_S, |x'| > b, \quad (9)$$

$$\varphi_{Cl} = 2k(n_{Cl} - n_S)\sqrt{b^2 - x'^2}, \quad (10)$$

$$\varphi_{Co} = 2k(n_{Co} - n_{Cl})\sqrt{a^2 - x'^2}, \quad (11)$$

where n_s is the index refraction of the fiber environment, n_{Cl} the refractive index of the cladding and n_{Co} the index refraction of the core; k is the wave number and a and b the internal and external radii of two concentric circles representing the cross sections of the fiber core and cladding. φ_{Su} takes into account the phase accumulated by the surroundings, φ_{Cl} the phase accumulated by the Cladding and φ_{Co} the phase accumulated by the Core. Now assuming that a unit amplitude wave is incident onto the fiber. U(x') can be evaluated as U(x') = exp($ik\varphi$), where φ takes into account at each point x' the different contributions of φ_{Su}, φ_{Co} and φ_{Cl} as described in [5]. The expression of the amplitude of the wavefield at a point P(x,y) (equation (5)) is finally:

$$\begin{aligned} U(P) &= \\ &= \frac{K'\exp(-i\varphi_{Su})}{B}\Big\{1 + C(\alpha) - C(\beta) \\ &+ i[1 + S(\alpha) - S(\beta)] \\ &+ B\left[\int_{-b}^{-a}\exp(-i\varphi_{Cl}(x'))exp\left[ik\frac{(x-x')^2}{2z'}\right]dx'\right. \\ &+ \int_{-a}^{a}\exp\{-i[\varphi_{Cl}(x') \\ &+ \varphi_{Co}(x')]\}\, exp\left[ik\frac{(x-x')^2}{2z'}\right]dx' \\ &+ \left.\int_{a}^{b}\exp(-i\varphi_{Cl}(x'))exp\left[ik\frac{(x-x')^2}{2z'}\right]dx'\right]\Big\}, \end{aligned}$$

where:

$$K' = \frac{Kexp(iz')}{\sqrt{\lambda z'}},$$

$$B = \frac{\sqrt{2}}{\sqrt{\lambda z'}},$$

$$\alpha = B(x - b),$$

$$\beta = B(x + b),$$

and $C(\alpha)$ y $S(\alpha)$ are the Fresnel integrals. The intensity as a function of x can then be calculated as: $I(x) = |U(x)|^2$.

2. Results and Discussion

Firstly, in Fig. 1 is shown the experimental set up used to obtain the diffraction patterns of rectangular apertures of different sizes and of the optical fiber. The light coming from an He-Ne laser (633 nm) is collimated by using a system of lenses; the sample (rectangular aperture or optical fiber) is placed between the laser and a CCD connected to a personal computer is used to process the data. Figs. 2 and 3 show the diffraction pattern obtained from two rectangular apertures pf sizes 120 and 175 μm respectively by using this set up.

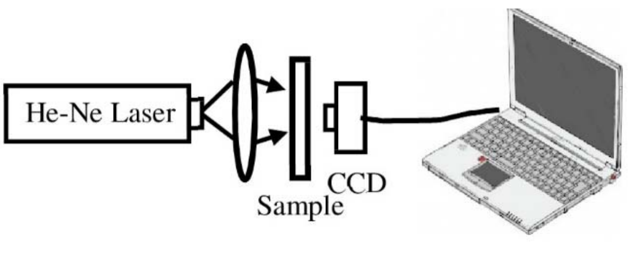

Fig. 1. Experimental set up used to record the diffraction patterns.

After recording the diffraction patterns of the different apertures, the data were normalized to unity. Since we were interested in the x dependence of the diffraction pattern a row of the corresponding 2D image matrix was chosen to perform the fitting of the theoretical curve. In Figs. 4, 5 and 6 the diffraction patterns obtained by placing a rectangular aperture, illuminated by a collimated beam of light coming from an He-Ne laser (633 nm), in front of a CCD camera are presented. The red line corresponds to Fresnel diffraction simulations of an aperture placed at a distance of 30 mm of the CCD, whereas the blue circles correspond to the experimental data. The values of the sizes of the apertures were 70, 120 and 175 μm. As can be seen from the figures there is good agreement between the theoretical curve obtained from equation (8) and the experimental data in the three cases. Moreover one can see the broadening of the curves in their bases with the increase in the size of the aperture.

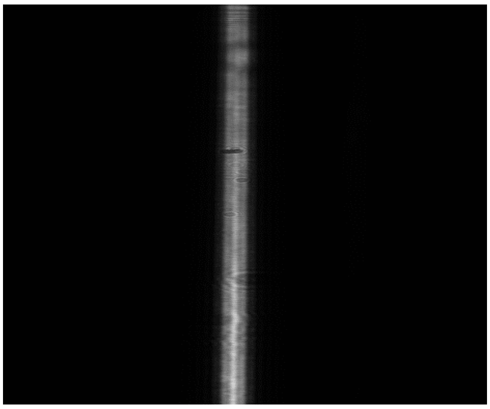

Fig. 2. Diffraction pattern on the CCD of rectangular aperture of 120 μm.

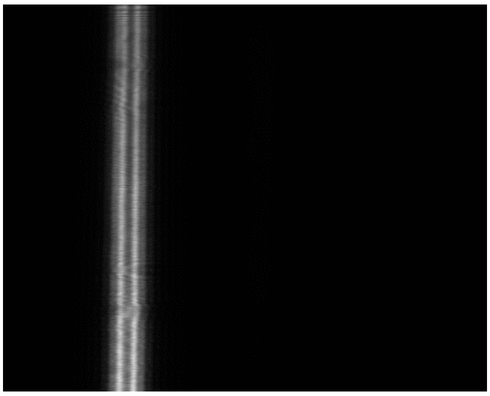

Fig. 3. Diffraction pattern on the CCD of rectangular aperture of 175 μm.

After calibrating the system by using the fitting to the theoretical diffraction patterns corresponding to the rectangular apertures the diffraction pattern of an optical fiber was recorded. In Fig. 7 the diffraction pattern recorded by a CCD of light coming from an optical fiber is shown.

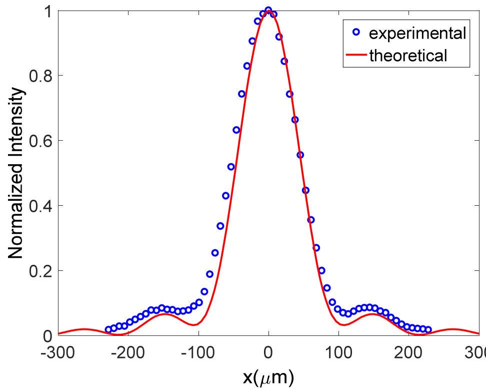

Fig. 4. Experimental and theoretical results of the diffraction pattern of a rectangular aperture of 70 μm.

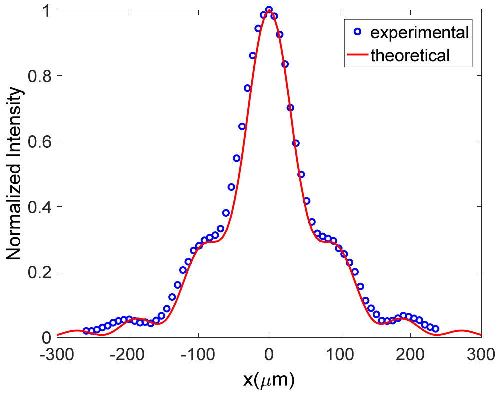

Fig. 5. Experimental and theoretical results of the diffraction pattern of a rectangular aperture of 120 μm.

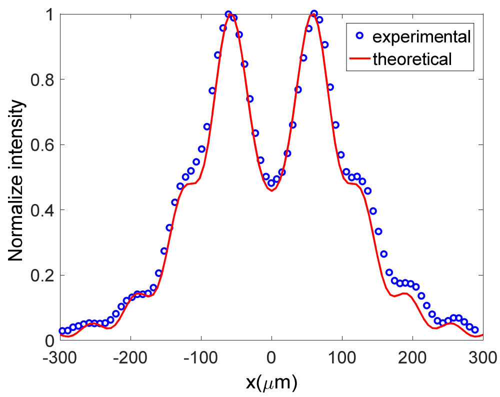

Fig. 6. Experimental and theoretical results of the diffraction pattern of a rectangular aperture of 175 μm.

Finally, Fig. 8 show the experimental data and the theoretical fit (in red) for the diffraction pattern of an optical fiber placed at 30 mm of the CCD. The results obtained from the fitting are shown in Table 1.

3. Conclusions

In this work a non-destructive technique based on Fresnel diffraction to obtain the refractive index profile of a fiber grating has been presented. The technique demonstrates great accuracy, with good agreement between experimental data and theoretical simulations.

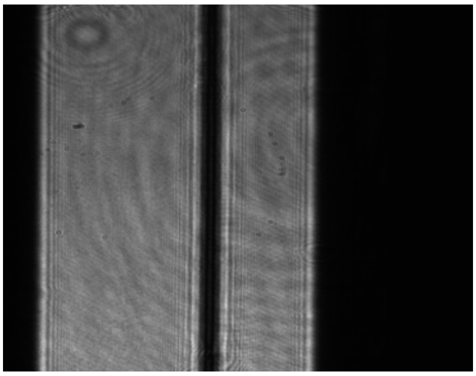

Fig. 7. Diffraction pattern on the CCD of an optical fiber.

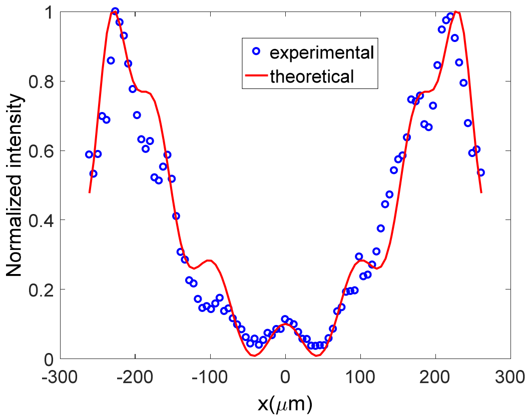

Fig. 8. Experimental and theoretical results of the diffraction pattern of an optical fiber.

Table 1. Parameters of the fiber obtained.

	Refractive index (n)	**Radius (μm)**
Core	1.459	25
Cladding	1.439	62

Acknowledgements

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