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Reflection-type Optical Waveguide Index Profiling Technique

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We report a new configuration of a reflection-type confocal scanning optical microscope system for measuring the refractive index profile of an optical waveguide. Several improvements on the earlier design are proposed; a light emitting diode (LED) at 650 nm wavelength instead of a laser diode (LD) or He-Ne laser is used as a light source for better index precision, and a simple longitudinal linear scanning and curve fitting techniques are adapted instead of a servo control for maintaining an optical confocal arrangement. We have obtained spatial resolution of 700 nm and an index precision of 2×10^{-4}. To verify the system's capability, the refractive index profiles of a conventional multimode fiber and a home-made four-mode fiber were examined with our proposed measurement method.

OCIS codes : 060.2270, 060.2300, 180.1790

I. INTRODUCTION

Ever since the development of index guided optical fibers and waveguides, various methods have been introduced to measure the refractive index profiles of optical waveguides and optical fibers [1]; the refracted near-field (RNF) method, the transverse interferometric (TM) method, and the transmitted near-field (TNF) method are conventional methods used for this purpose [2-4]. However, these methods have a critical drawback, in that a sample fiber or a waveguide needs to be immersed in an index-matching oil, and the observed refractive index profile is influenced by the index of the index-matching oil. Therefore, it needs a complicated sample preparation process, and the repeatability of a measurement is not normally very high.

In this paper, we describe a very simple and highly repeatable refractive index profile measurement technique using a modified confocal scanning optical microscope. As this method measures the change in reflectivity due to the change in the refractive index of a waveguide facet, it does not require any index-matching oil, and it is applicable to waveguides with complex and axially nonsymmetrical structures. Even though several research groups have used confocal microscope systems to measure refractive index profiles, these approaches were not very successful because of problems such as laser instability, noise in detection systems, and imperfections in sample surfaces [5-10]. By employing a stable LED source, a low signal detection system, and a scanning technique along the longitudinal axis with a simple data fitting process near the focal plane of a confocal system, we have obtained a high degree of refractive index precision and repeatability.

II. EXPERIMENT SETUP

The schematic diagram of our proposed refractive index profile measurement setup is shown in Fig. 1. An LED instead of an LD was used as an input optical light source to eliminate any unwanted effects from back reflections from the optical measurement setup. The fiber-coupled LED light is transmitted through a visible wavelength single mode fiber (SMF) and collimated with a lens system. This SMF makes the transverse beam profile of an LED circularly symmetric. A portion of the source power was measured using a detector (D1) after passing through a polarizing beam splitter (PBS) to monitor fluctuations in input optical power. The remainder of the source power was focused onto the end of the sample fiber using an objective lens.

The reflected light from the surface of the sample fiber was coupled back into the objective lens once again, and propagated in the backwards direction. The power of this reflected light was measured using another detector

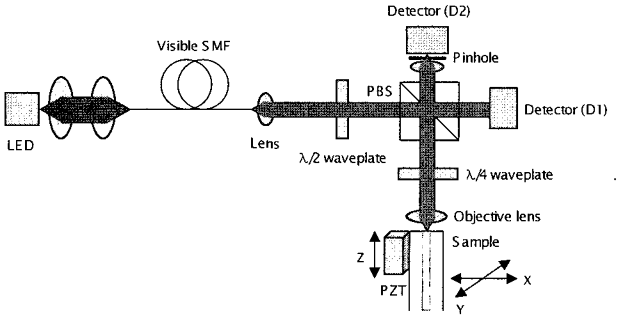


FIG. 1. Experimental refractive index measurement setup using a modified reflection-type confocal scanning optical microscope.

(D2) through a quarter-wave plate (QWP) and a polarizing beam splitter. The magnitudes of the transmitted and reflected light were collected while scanning a sample fiber surface transversely in the x-y plane to obtain a two dimensional (2D) reflected light intensity profile of a sample surface. The 2D reflectance profile along the transverse surface plane of a sample fiber was obtained by calculating the ratio of the input optical power and the reflected optical power. For a given scan point in the 2D transverse plane of a sample, the longitudinal position of a sample surface (z-axis) was varied with a PZT near the focal point of the focused beam. The reflected optical power was collected by D2, and it becomes maximum when the sample fiber's surface is at the focal plane of the input beam. The maximum reflected power value was acquired by fitting the reflected power versus the z-axis data. The reflectance of a sample fiber's surface can be related to its refractive index using the Fresnel equation, as shown in Equation (1). This was used to convert the obtained reflectance profile, $R(x,y)$, into the refractive index profile, $n(x,y)$, by assuming a normal incidence of the focused light onto the sample fiber's surface.

$$n(x,y)=\left(\frac{1+\sqrt{R(x,y)}}{1-\sqrt{R(x,y)}}\right) \qquad (1)$$

In a reflectivity measurement system, the stability of the optical source is important, because changes in the reflectivity associated with the refractive index fine structure of a sample can be masked by small power fluctuations occurring during the measurements. In our experiments, we have tested a He-Ne laser, an LD, and an LED as the light source of our confocal microscope system for measuring the refractive index. The conventional He-Ne laser source has a very fine spectral line width. However, its coherent length is very long such that interference from any optical component surface in our setup causes unpredictable intensity fluctuation in our measurement. The output power stability of an LD is normally very good and its power can easily be stabilized with an external feed-back loop to obtain better output stability. However the output power of an LD becomes unstable as soon as it is put in our confocal microscope system. This is because of the coupled cavity effect in an LD even with a very small amount of reflected light coupled back into the LD cavity. Therefore an LD does not seem to be a good choice for a reflection-type confocal intensity measure- ment system. To avoid any coherence-related power fluctuations in our measurement system, we have used an LED as the light source for our experiment. This light source is not sensitive to back reflections from various component surfaces in our system. Fig. 2. shows the normalized power fluctuation ratio of the detected reflected light intensity (δR/R) at a fixed reflection point on a sample in our confocal scanning optical microscope system for measuring the refractive index of optical waveguides. The data shown in Figs. 2 (a) and 2 (b) show that the normalized noise fluctuation ratio was about 0.8% for the LD and 0.1% for the LED sources, respectively.

Since the optical power of an LED coupled into a fiber in our system is very low, the sensitivity of measurement system is designed to be very high by using a low noise detector combined with a high-gain voltage amplifier. 16-bit digitization data acquisition (DAQ) board is employed with a narrow input range of 1 Volt. Fig. 3. shows the effect of digitizing error in acquired intensity data with the 16-bit DAQ board. The input data ranges of the DAQ board for traces 3 (a), 3 (b), and 3 (c) were ±10, ±5, and ±0.5 V, respectively. It shows that the actual intensity noise of data was below the sampling interval of the DAQ board in the case of

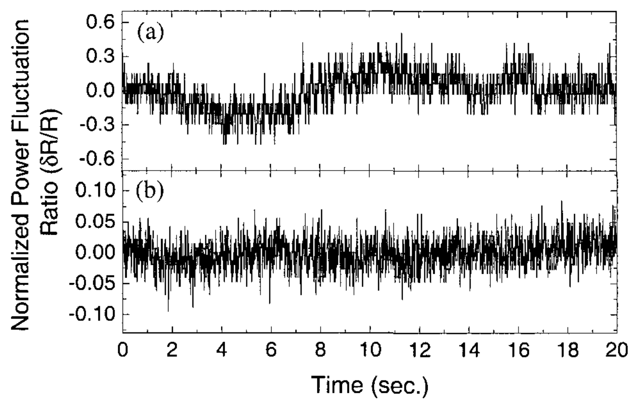


FIG. 2. Normalized power fluctuation ratio of the detected reflected light intensity (dR/R) in our confocal scanning optical microscope system for measuring the refractive index of optical waveguides. The noise fluctuation ratio was: (a) about 0.8% for a laser diode, and (b) 0.1% for a light emitting diode using a low signal detection system with a detected signal level of about 100 mV.

traces 3 (a) and 3 (b).

The transverse beam quality of the laser used in a confocal microscope system is very important, because the transverse beam shape is directly related to the spatial resolution of our measurement system. Instead of a prism pair or a pinhole, a 630 nm SMF was used to obtain a circularly symmetrical transverse beam profile. The light through a 1 m long visible SMF was collimated with a doublet lens to avoid spherical aberration. Fig. 4. shows a charge coupled device (CCD) image of the collimated beam whose FWHM diameter is about 3.6 mm after the visible SMF and the collimating lens. The spatial resolution of our confocal measurement system was determined by testing the spot size of the focused beam. The transverse optical power distribution at the focal plane of the focused beam is collected with a 100 nm size aluminum coated tapered fiber tip which is normally used in conventional nearield scanning optical microscopy. The FWHM of the input beam in the focal plane was about 700 nm.

The refractive index profile of a sample fiber could be obtained by moving the sample fiber while maintaining the confocal configuration with respect to the focused incoming beam. We have previously used a dithering servo control with a phase-locked loop to maintain the end facet of a sample at the focal point of the incoming beam in the scanning process [11]. This time, we measured the reflected power as a function of the longitudinal position z, for a fixed lateral position (x, y). Fig. 5 shows a typical measured reflected power as a function of longitudinal position z of a sample facet. The sample position is scanned by using a PZT actuator attached to a sample. We obtained the maximum reflected power when the sample facet was at the focal point of the incoming beam, where the incoming beam has a flat curvature such that the beam can be considered to be a plane wave. Using this x-y scanning process and a simple longitudinal scanning technique combined with a data fitting process, we could easily and directly obtain the two-dimensional (2D) refractive index profile of an optical fiber. In our measurement system, a QWP and a PBS were used as an optical isolator. The effect of back reflection from other surface, or the rear facet of a sample fiber, is eliminated by immersing the other end of a sample fiber in an index-matching oil.

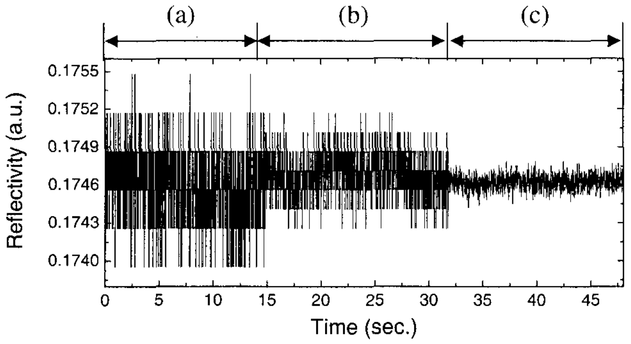
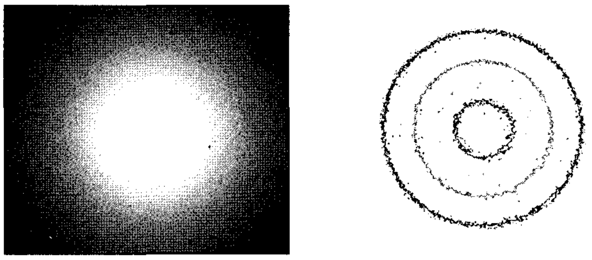


FIG. 3. Reflection power detection capability of the our detection system when the input data range of the 16-bit DAQ board is set (a) ±10, (b) ±5, and (c) ±0.5 V.



(a) (b)

FIG. 4. (a) CCD image of the collimated beam through a visible single mode fiber and a collimating lens, and (b) its contour plot.

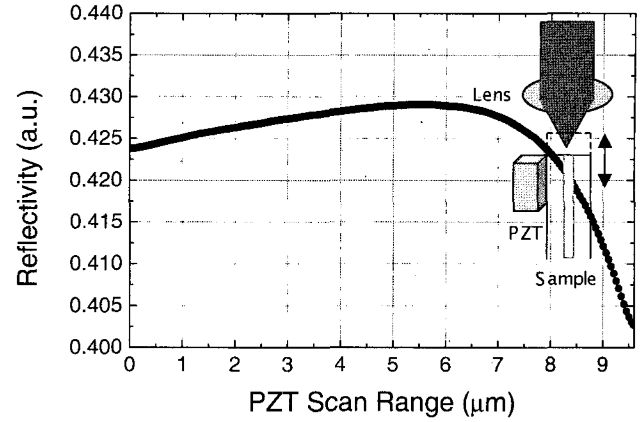


FIG. 5. Reflected power along the longitudinal distance z of the sample facet when it is changed by a PZT actuator attached to the sample. The maximum reflected power occurs when the sample facet is at the focal point of the incoming beam.

III. RESULTS

The refractive index profile of a standard 62.5 μm core graded index multimode fiber (MMF) was measured to demonstrate the effectiveness of our proposed measurement system. Fig. 6 shows the refractive index profile around the core region of the MMF. This refractive index profile was obtained from the measured reflectance profile. As the refractive index of the cladding material was known to be 1.4571, we used this value to calibrate the absolute value of the refractive index profile data. The solid curve shown in Fig. 6. denotes our measurements, and the dashed curve in Fig. 6. is for data obtained using a standard commercially available RNF instrument (S14, NETTEST Co.). These measurement results are consistent with each other. The refractive index profile of an another fiber is demon-

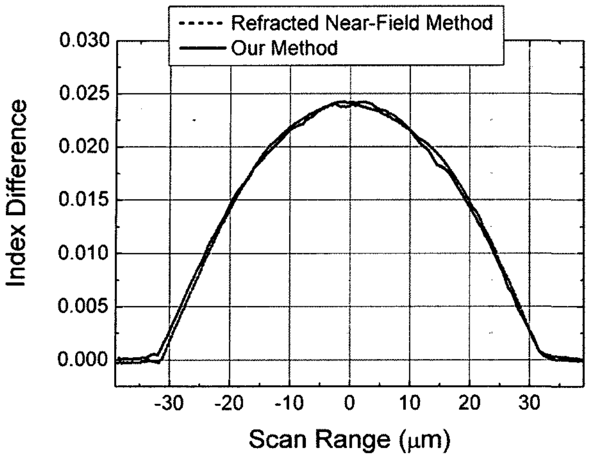


FIG. 6. Refractive index profiles of a conventional graded index fiber. The solid curve denotes our experimental data, while the dashed curve denotes experimental data from the standard RNF method.

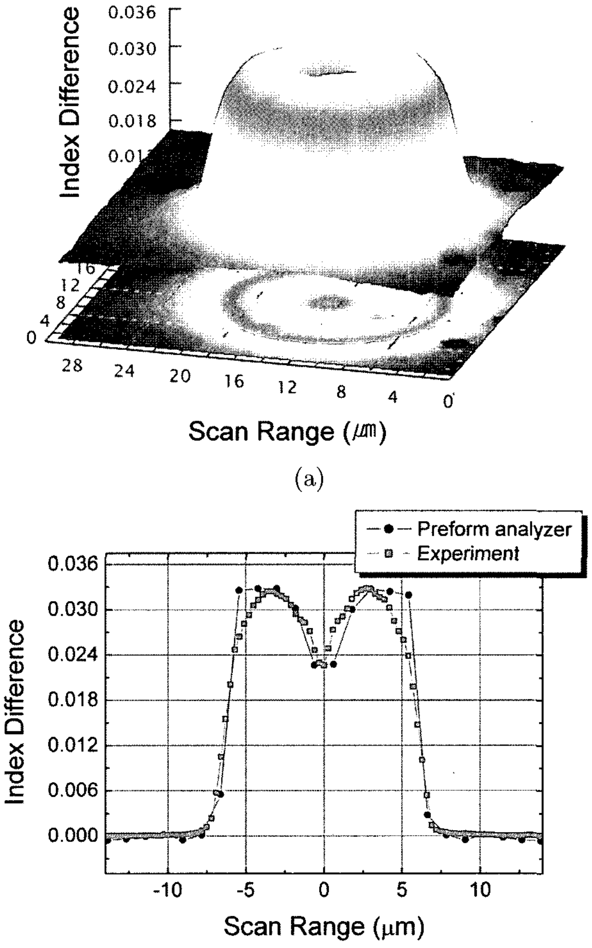
strated in Fig. 7. It shows the refractive index profile of a home-made four-mode step index MMF with a 13.4 μm core diameter. Difference in peak refractive index is measured to be 0.0328. The measurement scan area was 30×30 μm^2 with a step size of 300 nm. Fig. 7(a) shows the 2D index profile of the MMF measured with our method. Fig. 7(b) shows a comparison between our measurement results for a sample fiber and the refractive index of its preform measured using a conventional preform analyzer (P104, NETTEST Co.). The measured index profile for the preform has a much sharp edge profile near core-cladding boundary. It shows that the refractive index profile of the fiber perform is smoothened by diffusion process during a fiber drawing process. In our measurement system, 2D refractive index profile of a complex waveguide structure can be easily measured.

Errors in the measured refractive index profile can be calculated from the reflectance profile by using Equation (1). From Equation (1), the relative error of the difference in refractive index can be written as

$$\frac{\delta n}{n}=\left(\frac{n^2-1}{4n}\right)\frac{\delta R}{R} \qquad (2)$$

As the value of $\delta R/R$ is about -30 dB in our measurement system, and the cladding index of the MMF is about 1.4571, then the resolution of the refractive index measured with our proposed confocal microscope system is calculated to be about 2×10^{-4}.

IV. CONCLUSION



(a)

(b)

FIG. 7. (a) Two-dimensional index profile, and (b) one-dimensional index profile of a step index multimode fiber with a 13.4 μm core size and a difference in peak refractive index of 0.0328. The measurement scan area was 30×30 μm^2 and the 2D scanning step size was 300 nm.

A bulk confocal scanning optical microscope was modified to measure the refractive index profile. We have achieved an experimental index precision of 2×10^{-4} and a spatial resolution of 700 nm by employing a stable LED source, a low signal detection system, and a new vertical scanning technique combined with a curve fitting process in a confocal microscope system. Using this device, we have demonstrated measurements of the refractive index profiles of a conventional multimode fiber and a home-made four-mode multi- mode fiber.

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