Local Reconstruction of Birefringence in Bent Waveguides by Polarization-Sensitive Optical Low-Coherence Reflectometry

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Abstract. *Polarization-sensitive optical low-coherence reflectometry (PS-OLCR) is advantageously exploited to recover local birefringence evolution inside planar waveguides, with a micrometer spatial resolution. In particular, PS-OLCR characterizations on bent waveguides have experimentally highlighted a bend-induced birefringence dependence on the square of the radius of curvature.*

Introduction

Waveguide birefringence and related polarization dependent effects are an important and still open issue in integrated optical systems, particularly in silica-on-silicon planar waveguide technology, which can adversely affect device transfer function performances. Waveguide birefringence is defined as the difference between effective indexes of the two orthogonally polarized waveguide modes, that is, $\Delta n_{eff} = n_{eff}^{TM} - n_{eff}^{TE}$. Birefringence results from geometrical and stress-induced birefringence [1,2]. Yet, bent waveguide sections have been theoretically demonstrated to introduce a bend-induced birefringence [3,4] as a further contribution to the overall waveguide birefringence.

For a more comprehensive understanding of birefringence dependence on material and structural parameters, and for a more efficient waveguide design, measurement techniques providing a feedback of the actual birefringence are required. To this purpose, several methods have been introduces by previous art, yet, they are mainly limited by the fact that they provide only spatially averaged birefringence values, as they rely on an integral measurement along the waveguide length [5]. Thus, they do not allow to investigate the existence of local variation of birefringence inside the waveguide caused by defects of the manufacturing process, or induced on purpose. Moreover, if planar waveguides, including bent sections, have to be analyzed, these techniques can not cut out and estimate the contribution to birefringence due to curvature.

In the present work we have proved how polarization-sensitive optical low coherence reflectometry (PS-OLCR) [6] can be advantageously exploited to recover local birefringence evolution inside waveguides, with a micrometer spatial resolution, from the analysis of the state of polarization (SOP) of the backscattered light. In this way the PS-OLCR technique provides information on phase birefringence without suffering of the 2π-phase ambiguity. The peculiar features and potentialities of PS-OLCR have been demonstrated by characterizations carried out on bent waveguides which provided a first experimental evidence of a bend-induced birefringence dependence on the square of the waveguide radius of curvature.

The PS-OLCR experimental setup

Fig.1 shows a schematic of the PS-OLCR system realized in this work. It is basically a Michelson interferometer which detects the interference of a reference signal with the backscattered light from the waveguide under test. In order to analyze the birefringence-induced SOP evolution of the backscattered signal along the waveguide sample, the polarimetric scheme described in [6] has been conceived. In particular, in the detection arm the light is split into its horizontal and vertical components, with complex amplitudes A_H and A_V, by a polarization beam splitter (PBS) and focused onto two photodiodes to detect each single polarization. Since light from the reference arm, linearly polarized at 45° through the double passage through the λ/4 waveplate, is split equally into the horizontal and vertical polarization states, A_H and A_V result proportional to the light amplitude fields backscattered from the waveguide sample

$$A_H = \sqrt{R(z)}\, sin\left(k_0 z \Delta n_{eff}\right) e^{\left(\Delta z / l_c\right)^2} cos\left(2k_0 \Delta z + 2\phi\right)$$

$$A_V = \sqrt{R(z)}\, cos\left(k_0 z \Delta n_{eff}\right) e^{\left(\Delta z / l_c\right)^2} cos\left(2k_0 \Delta z\right) \tag{1}$$

where $k_0 = 2\pi/\lambda$, Δn_{eff} is the phase birefringence and ϕ the orientation of the birefringence axes. *R(z)* describes the reflectivity of the sample at depth z and the attenuation accumulated up to *z*, Δz is the optical path difference between the sample and reference arm of the interferometer and $l_c = \lambda^2/\Delta\lambda$ is the spatial coherence length of the light. In particular, the use of a broadband optical source ($\Delta\lambda \approx 30$nm, at λ=1.55μm), provides short coherence interference and results in a spatial resolution of $l_c/2n$ = 26μm, where *n* is the waveguide refractive index (*n*=1.5). The input signal is coupled to the waveguide under test by means of a 30x objective followed by a 15cm-long small-core fiber, with a 2μm core diameter. A piezoelectric transducer, attached to the small-core fiber, modulates the sample arm length by $\Delta z = \pm 1\,\mu m$ at a carrier frequency $f_c = 4kHz$, thus generating a frequency up- shifted interference signal whose components A_H and

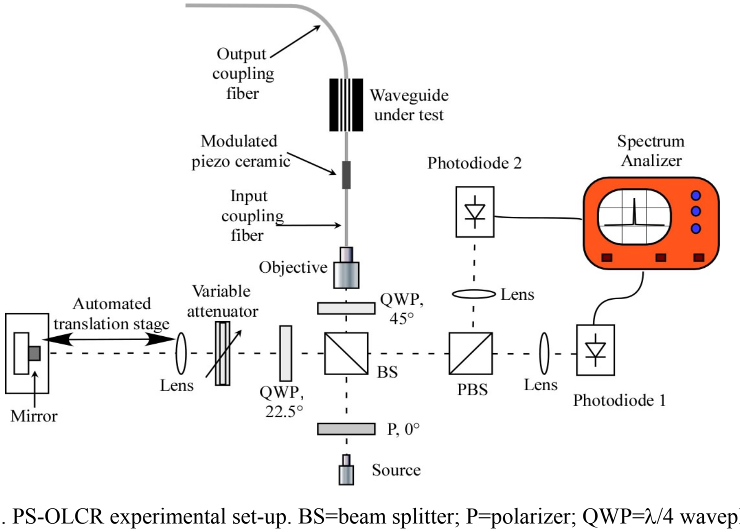


Fig. 1. PS-OLCR experimental set-up. BS=beam splitter; P=polarizer; QWP=λ/4 waveplate.

A_V are analyzed with a HP3585A electrical spectrum analyzer with a -63dBm sensitivity. According to [7], in order to improve the signal to noise ratio a variable attenuator was positioned in the reference arm to search for optimum attenuation of the reference power, which lead to a noise floor level of -55dBm. The power coupled to the waveguide was about 400μW, resulting in an averaged interference signal level of -40dBm, as detected by the photodiodes, that is, about 15dB above the noise floor. From the measurement of A_H and A_V at each backscattering point inside the sample, the evolution of the birefringence-induced phase retardation δ between the two-orthogonal polarization components could be retrieved by the following expression, simply derivable from (1)

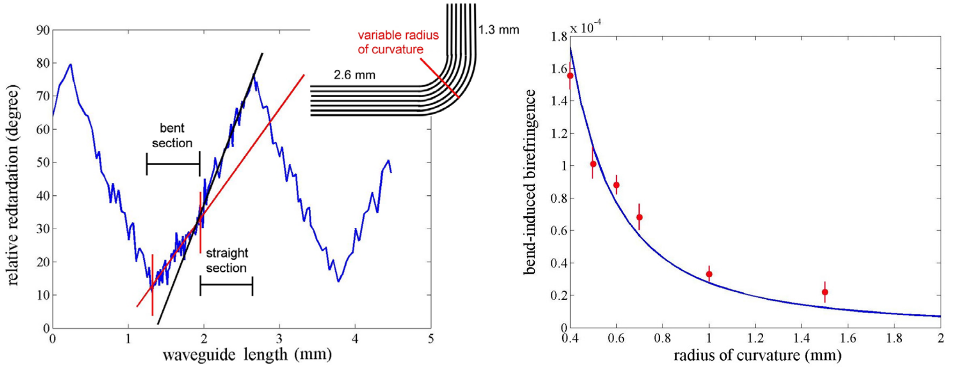
$$\delta(z) = \frac{2\pi}{\lambda} z \left| \Delta n_{eff} \right| = tan^{-1} \sqrt{I_H(z)/I_V(z)} \tag{2}$$

where $I_H = |A_H|^2$ and $I_V = |A_V|^2$ are the intensities of the two backscattered components. According to (2) phase retardation δ goes from 0° to 90° and from the slope of the retardation profile the local birefringence $\left| \Delta n_{eff} \right|$ inside the waveguide can be retrieved.

Experimental recovery of bend-induced birefringence

The feasibility and reliability of the PS-OLCR technique in waveguide birefringence recovery has been first verified by characterizing straight silica-on-silicon waveguides with different core widths. The measured birefringence values as a function of the core shape proved in good agreement with theoretical predictions [2]. Yet, to put into evidence the peculiarity of this technique with respect to other methods, which recover spatially averaged birefringence values, we have exploited the PS-OLCR set-up to characterize planar waveguide devices including bent sections. In particular we have analyzed a series of waveguides, as those shown in the inset of Fig.2(a), with the bent waveguides having radius of curvature R ranging from R=1.5mm to R=200μm. The waveguides featured a $2.2\times2.2\mu m^2$ SiON core and a SiO_2 cladding, with a contrast index Δn=4.4%. Fig.2(a) shows an example of birefringence-induced phase retardation profile reconstructed, by means of (2), along the waveguide length. Retardation profiles, as the one in Fig.2(a), were measured with backward steps of the reference arm of few tens of μm. Let's notice that, according to (2), retardation curves should range from 0° to 90°. The lower visibility in Fig.2(a) is mainly ascribable to the maximum achievable extinction ratio between the two polarization components of the backscattered signal, which in turn depends on the level of the backscattered signal with respect to the noise floor, that is, to the minimum detectable backscattered signal.

In Fig.2(a) the fitting lines indicate the slope of the birefringence-induced retardation profile in the bent section and in the subsequent straight waveguide section. It can be noticed that the effect of the curvature is to give rise to a bend-induced contribution that changes the overall waveguide birefringence, the effect having been measured to be more evident for smaller radii. A quantitative estimate of the bend-induced birefringence has been achieved by fitting measured data and comparing the slope of the retardation profile in bent and straight sections. Repeated measurements carried out on each waveguide, resulted in a standard deviation of ±1° in recovered slopes, thus proving the accuracy and reproducibility of retrieved birefringence values.



(a) (b)

Fig. 2. (a) Measured spatial behaviour of birefringence-induced phase retardation in a waveguide with a bent section of radius $R=400\mu m$. (b) Bend-induced birefringence as a function of the radius of curvature.

Results of bend-induced birefringence as recovered from characterizations of the above mentioned waveguides with different radius of curvature are reported in Fig.2(b). The fitting curve has a dependence on R^{-2}. Vertical bars represent the measurement uncertainties obtained from repeated phase retardation measurements. Thus, characterizations performed on bent waveguides with the PS-OLCR set-up fairly confirm theoretical predictions advanced in [3,4] which foresee a bend-induced birefringence proportional to the square of the waveguide radius of curvature.

Conclusions

It has been proven how PS-OLCR can be advantageously exploited to recover local birefringence evolution inside planar waveguides, with a micrometer spatial resolution. PS-OLCR may thus become a useful tool to investigate the existence of local variations, spurious or induced on purpose, of birefringence inside waveguides. The PS-OLCR peculiarity has been demonstrated by characterizations of waveguides including bent sections, as the contribution to birefringence due to curvature could be separated and put into evidence from the contributions of the straight waveguide sections. In particular, results have provided a first experimental confirmation of bend-induced birefringence dependence on the square of the waveguide radius of curvature.

References

[1] M. Huang, "Analytical solutions for thermal stresses in buried channel waveguides," *IEEE J. Quantum Electron.,* vol. 40, pp. 1562-1568, 2004.

[2] K. Okamoto, *Fundamentals of Optical Waveguides*. New York: Academic, 2000.

[3] F. Morichetti, A. Melloni, M. Martinelli, "Effects of polarization rotation in optical ring-resonator-based device," *IEEE J. Ligthwave Technol.*, vol. 24, pp. 573-585, 2006.

[4] A. Melloni, F. Carniel, R. Costa, M. Martinelli, "Determination of bend mode characteristic in dielectric waveguides," *IEEE J. Ligthwave Technol.*, vol. 19, pp. 571-577, 2001.

[5] S.Y. Cheng, K.S. Chiang, H.P. Chan, "Birefringence in Benzocyclobutene strip optical waveguides," *IEEE J. Photon Technol.*, vol. 15, pp. 700-702, 2003.

[6] J.-T. Oh, S.-W. Kim, "Polarization-sensitive optical coherence tomography for photoelasticity testing of glass/epoxy composites," *Opt. Express*, vol. 11, pp. 1669-1676, 2003.

[7] W.V. Sorin, D.M. Baney, "A simple intensity noise reduction technique for optical low-coherence reflectometry," *IEEE J. Photon. Technol.*, vol. 4, pp. 1404-1406, 1992.