Characterization of the Large Index Modification Caused by Electrical Discharge in Optical Fibers

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Abstract: The large index perturbation observed in Long Period Gratings made by electric discharge is measured and explained in terms of modification of the fiber stress and strain state.

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1. Introduction

It is known that electric discharges such as those used to splice fibers can change the local glass structure and modify its refractive index. Long Period Gratings (LPG) made in a standard and microstructured single-mode fibers have beeen manufactured using this technique [1]. Refractive index changes ranging from a few 10^{-4} to values as large as $\Delta n \approx 2 \cdot 10^{-3}$ have been evaluated from the LPGs spectral transmissions [2,3]. Several explanations have been proposed for this large index modification, such as densification, dopant diffusion and micro-tapering. However, we have not observed measurable fiber diameter modulation under the microscope even on efficient LPGs. More importantly, refractive index profile measurement using the Refracted Near Field (RNF) method have failed to detect dopant diffusion and index modifications above the 10^{-4} sensitivity threshold of our setup. The remaining probable explanation for efficient LPGs by electric discharge is the induction of large modification of the internal stress in the fiber. This large stress may be relaxed when the fiber is cleaved prior to the RNF measurement, thereby preventing a direct measurement of the index modification. We herein present direct index anisotropy measurements of uncleaved SMF28$^{\mathrm{TM}}$ fibers which confirm this hypothesis.

2. Experiment

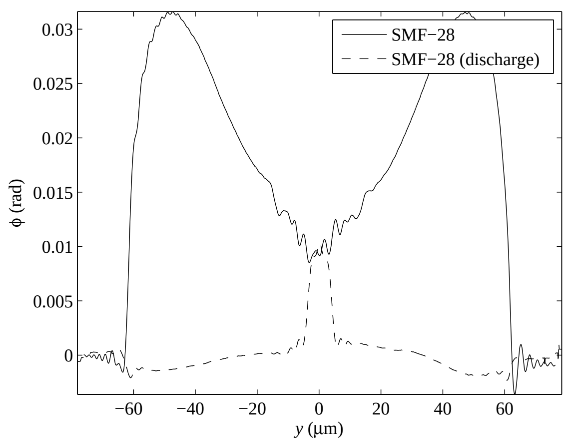
The index anisotropy of a Corning SMF-28$^{\mathrm{TM}}$ fiber was characterized before and after an electric discharge had been applied. The discharge parameters are typical of those used for splicing. Index anisotropy is measured through the phase retardation ϕ between light polarized along the longitudinal z axis (fiber axis) and the transverse y axis when propagating through the fiber from the side along the x axis. The measured phase retardation may be expressed as

$$\phi(y) = \frac{2\pi}{\lambda} \int_{-\sqrt{R^2-y^2}}^{+\sqrt{R^2-y^2}} \beta(x,y)\mathrm{d}x \qquad (1)$$

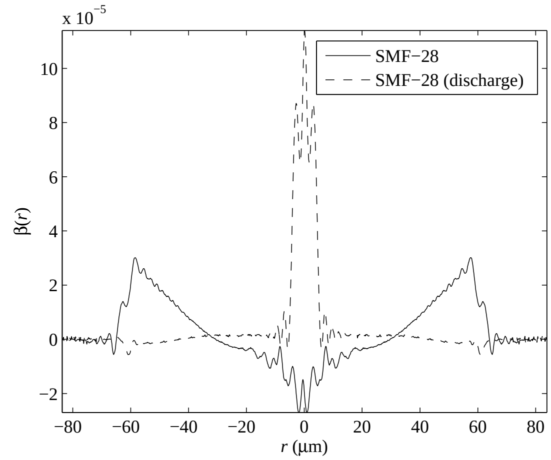
where R is the fiber radius and β is explained below. Fig. 1(a) shows the measured phase retardation ϕ as a function of y for a pristine Corning SMF-28$^{\mathrm{TM}}$ fiber and for the same fiber after an electric discharge had been applied to it. Fig. 1(b) shows the $\beta(r)$ parameters obtained from the ϕ measurements through an inverse Radon transform.

The main feature to be observed in the pristine fiber raw measurement is that $\int_{-R}^{+R} \phi(y)\mathrm{d}y \neq 0$. We conclude that β consists not only of an elastic term but also of a residual term of viscoelastic origin. To support this affirmation, let's remember that the elastic term is proportional to the longitudinal stress σ_z through C, the stress-optic coefficient: $\beta_{\mathrm{el}} = C\sigma_z$ [4]. Mechanical equilibrium requires $\int_A \sigma_z \mathrm{d}x\mathrm{d}y = 0$. The β parameter that we retrieve must therefore include a residual inelastic term. It can be written as $\beta_{\mathrm{res}} = P\Delta\epsilon_{\mathrm{res}}$, where P is the strain-optic coefficient [5] and $\Delta\epsilon_{\mathrm{res}}$ the frozen-in strain anisotropy, i.e, the difference between the longitudinal ϵ_z and the transverse isotropic $\epsilon_\perp$ viscoelastic strains [6]. The residual stress contribution appears in the β curve of Fig. 1(b) as characteristic wings near the external cladding interface, where cooling occured first during fiber drawing. The core is also clearly visible in this β profile with oscillations in the signal mainly due to diffraction effects. The diffraction fringes at the external medium-cladding interface were properly eliminated by the use of a matched index liquid as the external medium.

After the electric discharge had been applied, the ϕ profile is totally different. Since the integrals $\int_{-R}^{+R} \phi(y)\mathrm{d}y$. and $\int_0^R \beta(r)r\mathrm{d}r$ vanish, it suggests that $\beta(r) = \beta_{\mathrm{el}} = C\sigma_z$ and thus that the residual viscoelastic strain $\Delta\epsilon_{\mathrm{res}}$ has been annealed. After the discharge, the phase retardation is mainly of elastic origin. It is related to the radial distribution of the thermal expansion coefficient α [7] and the axial stress σ_z is expected to follow the core-cladding α step



(a)



(b)

Fig. 1: (a) measurements of $\phi(y)$ for a Corning SMF-28$^{\mathrm{TM}}$ fiber before and after a discharge had been applied to it. (b) β profiles of a Corning SMF-28$^{\mathrm{TM}}$ fiber before and after a discharge had been applied to it. These profiles are computed from the measurements of the birefringence phase retardation ϕ. Before the discharge the value of β is expected to comprise two terms $\beta = C\sigma_z + P\Delta\epsilon$ whereas only the elastic term $\beta = C\sigma_z$ remains after the discharge annealing.

$\Delta\alpha = \alpha_{\mathrm{cl}} - \alpha_{\mathrm{co}}$ where "cl" and "co" refer to the fiber cladding and core respectively:

$$\sigma_z^{\mathrm{co}} = \frac{E}{1-\nu}\Delta\alpha\Delta T\left(1 - \frac{R_{\mathrm{co}}^2}{R_{\mathrm{cl}}^2}\right), \qquad \sigma_z^{\mathrm{cl}} = -\frac{E}{1-\nu}\Delta\alpha\Delta T\frac{R_{\mathrm{co}}^2}{R_{\mathrm{cl}}^2} \tag{2}$$

where $\Delta T = T - T_g$ the difference between the room and the glass transition temperature, E and ν are the Young's modulus and Poisson's ratio of silica respectively. According to Eq. 2, the stress σ_z is expected to be uniform in each layer. After the discharge, we indeed observe that β is roughly uniform in each layer, which supports our interpretation. Data appearing in Fig.1(b) suggest that the core is in a tensile longitudinal stress state, which is to be expected for a silica fiber with a Ge-doped core. Finally, from the ϕ measurements and β profiles before and after the electric treatment, one can retrieve the variation of the index step due to the discharge. From the data of Fig.1(b), we estimated a decrease of the order of 10^{-4}. Because of the diffraction fringes, this value is only a rough estimation but it is the order of magnitude of the refractive index change often reported in the litterature [1,2].

3. Conclusion

We herein reported index anisotropy measurements on a Corning SMF-28$^{\mathrm{TM}}$ fiber before and after an electric discharge has been applied to it in a fusion splicer. Measurements show evidence of frozen-in viscoelastic strains in the pristine fiber that are annealed by the discharge. This annealing results in an estimated index step decrease of the order of 10^{-4} for our set of parameters, a value sufficient to manufacture efficient LPGs by using the electric discharge technique.

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