# Micro- and Nanostructure Induced Birefringence in Phosphate Glass Fibers

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**Abstract:** We demonstrate that microstructures inside the cladding of phosphate fiber as well as sub-wavelength nanostructures inside the fiber core can introduce birefringence in phosphate glass fiber components.

OCIS codes: (060.2280) Fiber design and fabrication; (260.1440) Birefringence; (140.3510) Fiber lasers.

## 1. Introduction

The invention of microstructured optical fiber (MOF) [1] has opened new avenues for the design of fiber optic components and devices. The most widely applied types of MOF feature a cladding with a periodic pattern of different dielectrics. The microstructure enables to select the wavelengths of light that can propagate with low losses and also determines the characteristics of the supported modes in terms of field distribution, propagation constant, and dispersion. Almost all glass MOF are based on silica and attempts to use non-silica glasses are still rare [see e.g. 2 and references therein]. Although propagation losses in non-silica MOF are typically higher, they can offer special properties that might be advantageous for applications including active fiber with high solubility of rare-earth ions.

Here we will present our efforts to fabricate and characterize optical fibers based on phosphate glasses that include structures on the micro- and nanometer scale to induce birefringence. We developed techniques to fabricate phosphate glass fiber that incorporate a variety of structures including air holes of different sizes and shapes, highly doped solid cores, and also cores consisting of different glasses that can be arranged in suitable patterns to achieve specific properties.

## 2. Birefringent active phosphate glasses fiber with microstructured cladding

A highly desirable feature for many applications is the guidance of light while maintaining its polarization state. Traditional polarization maintaining fiber, such as Panda or bow-tie types, contain different glasses with different thermal properties, a characteristic that is detrimental in applications where heat is generated such as fiber lasers.

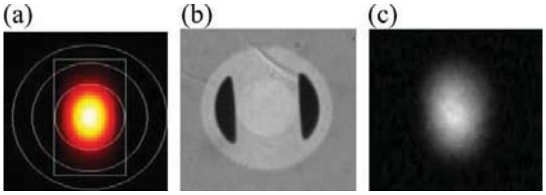

Fig.1. (a) Calculated eigenmode of the designed active birefringent fiber. (b) Cross-sectional image of the fabricated fiber zooming in on the area around the active core (bright central area) with air holes (dark areas) in close vicinity to the core. (c) Mode profile measured 63 cm from a fiber laser output facet using the birefringent fiber with doped phosphate glass core.

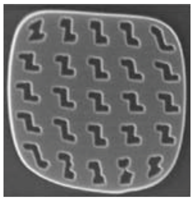

Fig. 2. (a) SEM image of a fiber facet. Shown is the area around the 5.2 mm x 5.2 mm core that comprises two different glasses arranged in a pattern with feature sizes smaller than the wavelength of light.

An alternative approach is to design a microstructured fiber with structural birefringence or birefringent supermodes [3]. Structural birefringence can be even higher than stress-induced birefringence in Panda or bow-tie fibers. Even absolutely single-polarization fiber has been developed utilizing microstructured fibers. In many fiber laser applications single-polarization emission is required. To achieve this characteristic it is not always necessary but highly beneficial to have active fibers that are polarization maintaining. Therefore, we designed and fabricated a birefringent active phosphate glass fiber that is shown in Fig. 1. With two large air holes in close vicinity of the core, the fiber design is similar to recently demonstrated single-polarization fibers. However, our design features a circular core resulting in a more circular fundamental mode that is presented in the calculated and measured modes profiles shown in Fig. 1 (a) and (c). There is a trade-off between the degree of birefringence and the deviation of the mode from circular symmetry. In contrast to previous designs, in our case both the calculated and the measured mode shapes closely resemble a Gaussian profile in both vertical and horizontal directions, but there still is a difference in the mode waist; the vertical waist is about 50% larger than the horizontal one. The inner cladding contains 2 air holes on opposite sides of the core that get as close as ~0.1 μm to the. The presence of these air holes results in a difference in the modal indices for the two orthogonal polarization states of $\Delta n=9\text{x}10^{-5}$ at 1.55 μm. The core of the fiber is highly Er/Yb co-doped and we will demonstrate the use of this fiber to fabricate a single-polarization fiber laser.

## 3. Birefringence induced by sub-wavelength dielectric structures inside a phosphate glass fiber core

Considering the trade-off between mode field distribution and structural birefringence in MOFs, alternatives are sought for highly birefringent fibers that allow for mode fields compatible with conventional optical fibers. Here we propose and explore a different approach based on the incorporation of a periodic dielectric structure directly into the core [4]. Fabricating cores with sub-wavelength modulations of the refractive index results in the creation of a birefringent effective medium that forms the fiber core.

We test this approach using a phosphate glass fiber that has a standard outer diameter of 125 μm and a small, almost square core with a size of 5.2 μm x 5.2 μm. A SEM image of the fiber core is shown in Fig. 2. The core consists of a dielectric structure fabricated using two glasses that are visible as light and dark regions, respectively. The fiber features a near-Gaussian single-mode guidance at 1.55 μm with a birefringence of $\Delta\beta=(0.064\pm0.001)/\text{cm}$, corresponding to a refractive index difference of $\Delta n\sim1.5\text{x}10^{-6}$ and a beat length of $L_B=2\pi/\Delta\beta\sim1$ m. The demonstrated birefringence might be small, but this first attempt should be considered a starting point for optimizing individual features, there arrangement, and the materials to make this concept useful for practical applications.

This work was supported by the National Sciences Foundation through Grant No. 0725479.

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