MEASUREMENT OF THERMAL DEPENDENCIES OF PBG FIBER PROPERTIES

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Abstract

Photonic crystal fibers (PCFs) represent a class of optical fibers which have a wide spectrum of applications in the telecom and sensing industries. Currently, the Advanced Accelerator Research Department at SLAC is developing photonic bandgap particle accelerators [1], which are photonic crystal structures with a central defect used to accelerate electrons and achieve high longitudinal electric fields. Extremely compact and less costly than the traditional accelerators, these structures can support higher accelerating gradients and will open a new era in high energy physics as well as other fields of science. Based on direct laser acceleration in dielectric materials, the so called photonic band gap accelerators will benefit from mature laser and semiconductor industries.

INTRODUCTION

One of the key elements to direct laser acceleration in hollow core PCFs, is maintaining thermal and structural stability. Previous simulations demonstrate that accelerating modes are sensitive to the geometry of the defect region and the variations in the effective index. Unlike the telecom modes (for which over 95% of the energy propagates in the hollow core) most of the power of these modes is located in the glass at the periphery of the central hole which has a higher thermal constant than air (γ_{SiO2}=1.19x10^{-6} 1/K, γ_{air}=-9x10^{-7} 1/K with γ=dn/dT).

To fully control laser driven acceleration, we need to evaluate the thermal and structural consequences of such modes on the PCFs. We are conducting series of interferometric tests to quantify the dependencies of the HC-633-02 (NKT Photonics [2]) propagation constant (k_z) on temperature, vibration amplitude, stress and electric field strength.

In this paper we will present the theoretical principles characterizing the thermal behavior of a PCF [3], the measurements realized for the fundamental telecom mode (TE_{00}), and the experimental demonstration of TM-like mode propagation in the HC-633-02 fiber.

THERMAL CONSTANT

For accelerator applications, maintaining synchronism between beam and phase velocity of the modes propagating along the fiber is a critical issue for the performance of an accelerator. PCF structures are expected to range from 100λ-1000λ in length, requiring precise control of the phase velocity. Therefore, the thermal response of this type of fibers needs to be fully understood and tightly controlled.

The phase stability of an optical signal is determined by three effects:

- Thermo-optic effect or the temperature induced variation of refractive index in the glass and in the air filling the holes
- Thermal expansion of the fiber. Indeed, as the temperature increases, the fibers expands radially and longitudinally inducing a change in the effective mode index and a phase delay as the optical signal travels along the fiber.
- Nonlinearities caused by high field intensities in the glass.

Thus, to quantify the phase dependencies of a supported optical mode on temperature; one can define a thermal constant S:

$$S = \frac{1}{\phi}.\frac{d\phi}{dT}$$

Where T is the temperature of the fiber, and the phase ϕ accumulated by an optical mode as it propagates along the fiber is given in terms of the effective mode index n_{eff} fiber length L and accelerating wavelength λ by:

$$\phi = \frac{2\pi . n_{eff} . L}{\lambda}$$

If one differentiates the expression of ϕ with respect to temperature, one can define two other constants S_n and S_L, which characterize the thermo-optic effect on one hand, and the phase delay of an optical signal caused by the longitudinal thermal expansion of the fiber on the other:

$$S = \frac{1}{n_{eff}}.\frac{dn_{eff}}{dT} + \frac{1}{L}.\frac{dL}{dT} = S_n + S_L$$

EXPERIMENTAL SETUP

The measurements of the thermal S parameter for the HC-633-02 from NKT Photonics (SEM image Fig. 1) were carried out using a hybrid freespace/fiber Mach-Zehnder interferometer (see Fig. 2). The signal source in this experiment is a red HeNe laser at 633nm with a coherence length of a 100m. The hollow core fiber was connectorized with FC-connectors on both ends and secured in a micro positioning Thorlabs fiberport to form the sensing arm. The built-in aspheric lens can be aligned

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with five degrees of freedom (linear alignment x, y and z-axes and angular alignment for tip and tilt) to maximize the coupling efficiency (about 30%) in a very compact and stable way. The 30cm long segment of fiber under test, was secured with an aluminium cylinder in a 15cm long column heater to provide good thermal conduction and keep the temperature distribution inside the fiber as uniform as possible. The heater used in this experiment is an HPLC column with a temperature stability of ±0.1°C.

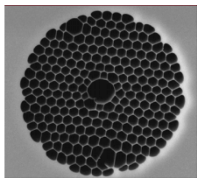

Figure 1: SEM image of the HC-633-02.

To reduce the influence of small temperature changes in the reference arm, we raised the temperature of the fiber from room temperature up to 50°C, which induced a phase change equivalent to 70-90 fringes.

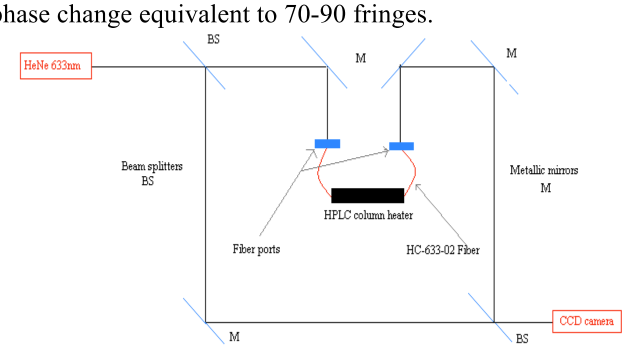

Figure 2: Interferometer setup.

This interferometric configuration happens to be extremely sensitive to vibrations. Indeed, even though the setup was secured on an optical table, separate geophone measurements showed low vibrations amplitudes as small as ~30nm horizontally and ~45nm vertically. To circumvent this issue, the interferometer was placed on vibration isolating pads to absorb the undesirable vibrations.

To measure the thermal S parameter, the heater was programmed to raise the temperature up to 50°C. This temperature was reached after ten minutes on average. Meanwhile, a CCD camera detects the induced phase shift and a Labview program was used to count the number of fringes by computing the FFT of a lineout from the camera through the fringe pattern, and by tracking the phase of the frequency component corresponding to the fringe pattern.

The thermal constant S was calculated from the measured number of fringes N until the temperature stabilizes using:

$$S = \frac{\lambda.\Delta\phi}{2\pi.n_{eff}.L.\Delta T} \approx \frac{N}{n_{eff}.L.\Delta T / \lambda}$$

Where L is the length of the fiber under test (15cm) and ΔT is the temperature change occurring in the fiber during the measurement.

The approximation $\frac{d\phi}{dT} \approx \frac{\Delta\phi}{\Delta T}$ has been verified by increasing the temperature in the fiber in increments of 5ºC from room temperature up to 50ºC and compare the results to those obtained by heating the fiber up directly from room temperature to 50ºC. The discrepancy between the results was about 5%.

Moreover, the thermal equilibrium was reached rapidly enough that any external phase shifts from random temperature changes in the rest of the interferometer were negligible. This last point was verified by recording the interferometer output over a period of 30 minutes (3 times longer than the heating process) during which the total phase deviation varied by less than 1 fringe. The recorded phase variation during a 50ºC heating cycle is displayed in Fig. 3.

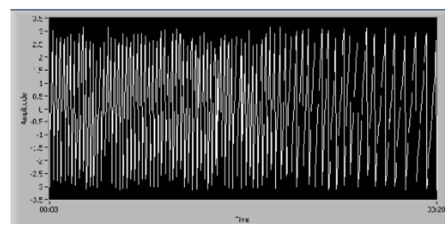

Figure 3: Thermally induced phase shift of HC-633-02 fiber over 25-50 ºC heating cycle.

EXPERIMENTAL RESULTS

As a point of comparison, we will use the measurements done for the HC-1550-02, a scaled version of the HC-633-02 fiber, by the Ginzton laboratory at Stanford University [2].

The geometrical characteristics of both fibers are summarized in Table 1.

Table 1: Geometrical Characteristics (Diameters)

Region	HC-633-02	HC-1550-02
Coating jacket	220 um	270 um
Cladding	102 um	185 um
Honeycomb	37 um	67 um
Core	5.8 um	10 um

Since the geometrical characteristics of the HC-1550-02 are approximately twice as large as the HC-633-02, one can expect the thermal constant of the first fiber to be, at least half the second one. Indeed the measured S of the HC-633-02 (S=8.9ppm±0.6\°C) is about four times higher that thermal constant of the HC-1550-02 (1.5ppm±0.9\°C) which is consistent with the predictions.

As the fundamental mode is mostly confined in the hollow core, the physical expansion coefficient S_L plays a much larger role than the thermo-optic coefficient S_n. Since the acrylate of the jacket has a much higher thermal expansion coefficient (α_{jacket}=80x10^{-6} 1/K) than the fused silica of the honeycomb and the cladding region ($\alpha_{fusedSilica}$=0.55x10^{-6} 1/K), one can safely assume that the main contribution to S_L is due to the thermal expansion of the jacket.

Since future fiber based accelerator devices, won't be coated, it is interesting to evaluate the factor by which S would be reduced if we consider only the fused silica cladding. Using COMSOL Multiphysics, we conducted thermo-elastic simulations for the HC-633-02 fiber without the jacket. Limited by computer memory, the segment of fiber was 10um long and 60um diameter. In the model, the fiber was heated uniformly on its outer boundary. The plot in Fig. 4 display the longitudinal displacement induced by a 10°C increase of temperature (ΔT=30-20°C).

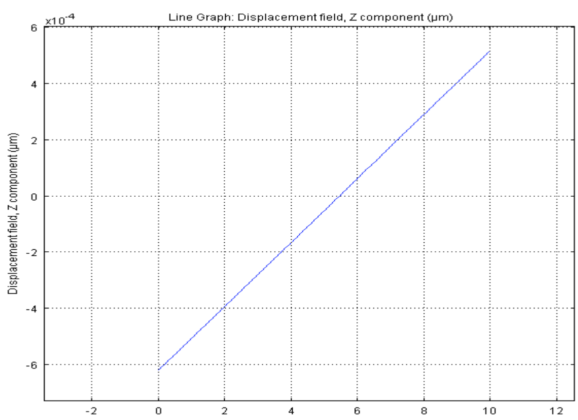

Figure 4: Longitudinal displacement field.

In this configuration the fiber stretched by 5.1x10^{-4}um. Therefore, considering that we are operating in the elastic region of fused silica:

$$S_L = \frac{1}{L}.\frac{dL}{dT} = \frac{1}{L}.\frac{\Delta L}{\Delta T} = 5.1 ppm/{}^\circ C$$

Since the diameter of the simulated segment is twice as large as the diameter of the real fiber, the S_L constant of the actual HC-633-02 without the jacket should be around 2.5ppm/ºC. Thus by removing the polymer jacket, one can reduce the influence of temperature on the phase by a factor of 3, assuming that the thermo-optical effect is negligible.

EXPERIMENTAL OBSERVATION OF A TM-LIKE MODE SUPPORTED BY THE HC-633-02 FIBER

As mentioned earlier, accelerating modes are mostly localized in the glass, at the surface of the main defect. Therefore, one can expect such modes to be much more sensitive to temperature than the telecom fundamental core mode. In order to estimate their thermal dependencies we first experimentally confirmed the existence of a supported radially-polarized TM_{01*} core mode in the HC-633-02.

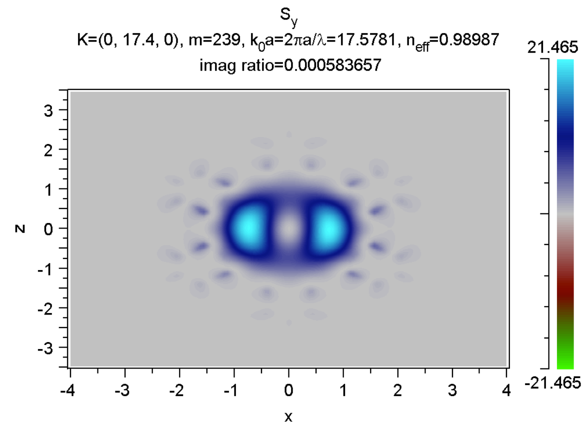

Figure 5: RSoft eigenmode simulations of the TM_{01*} mode, showing the axial Poynting flux

To generate the TM_{01*} mode we used a liquid crystal mode converter that converts the TE_{00} mode from the HeNe laser.

After checking that the output signal of the fiber was radially-polarized with a polarizer, we image the near field distribution with a 100x microscope objective (see Fig. 6).

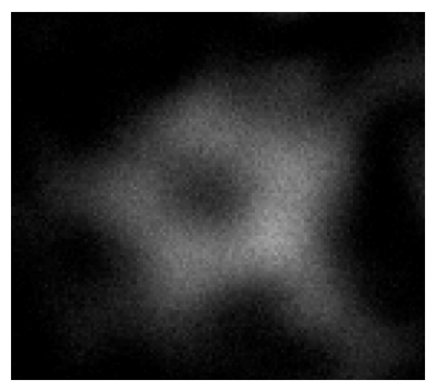

Figure 6: Near field mode profile of transmitted $\mathbf{TM_{01*}}$ mode.

ONGOING AND FUTURE WORK

Currently we are setting up the interferometer to measure the thermal constant of the TM_{01*} mode supported by the HC-633-02. Ultimately, we will make pulsed interferometric measurements to study the intensity-dependent nonlinearities of candidate fibers which support accelerating modes.

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