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Anti-Resonant Hollow Core Fiber for Precision Timing Applications

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ABSTRACT

Many applications rely on the ultra-precise timing of optical signals through fiber, such as fiber interferometers, large telescope arrays, in phase arrayed antennae, optical metrology, and precision navigation and tracking. Environmental changes, specifically those caused by temperature fluctuations, lead to variations in the propagation delay of optical signals and thereby decrease the accuracy of the system's timing.

The cause of these variations in delay is the change in the glass properties of the optical fiber with temperature. Both the refractive index of the glass and the length of the fiber are dependent on the ambient temperature. Traditional optical fiber suffers from a delay sensitivity of 39 ps/km/K. We are reducing the temperature sensitivity of the fiber delay through the application of a novel design of optical fiber, Anti-Resonant Hollow Core Fiber. The major improvement in the thermal sensitivity of this fiber comes from the fact that the light is guided in an air core, with very little overlap into the glass structure. This drastically reduces the impact that the thermally sensitive glass properties have on the propagation time of the optical signal. Additionally, hollow core fiber is inherently radiation insensitive, due to the light guidance in air, making it suitable for space applications.

Keywords: optical fiber, hollow core fiber, fiber fabrication

1. INTRODUCTION

Traditional optical fiber suffers from timing instabilities caused by thermal fluctuations. For applications requiring high precision, such as optical metrology or large telescope arrays, these thermal fluctuations can severely affect their accuracy.

Current mitigation methods for reducing this delay include the use of active stabilization using the backward propagating signal or an additional fiber loop. However, these methods add significant cost and complication to the system[1]. Another common method of mitigating thermal sensitivity of optical fiber is through the use of a specialty coating which counteracts the length change effect. These coatings are made from a liquid crystal polymer with a negative thermal expansion coefficient, and have been shown to reduce the delay sensitivity from 39 ps/km/K to 3.7 ps/km/K, but are only functional up to a temperature of 100°C.

An alternative solution for reducing the temperature sensitivity of optical fiber is using hollow core fiber. Hollow core fibers (HCF) are optical fibers that guide light in an air core, as opposed to a solid material, such as glass. Eliminating the glass from the core of the fiber greatly reduces the effect of temperature on the propagation of the light in the fiber, due to nearly eliminating the effect of the glass refractive index changing with temperature.

There are several different types of HCF which operate on different guiding principles. Instead of total internal reflection, some HCF types use alternate guiding mechanisms such as the anti-resonant[2–6] or photonic bandgap effects[7,8]. It has been shown that photonic bandgap hollow core fiber (PBGHCF) can significantly reduce the sensitivity without using special coatings [9,10]. A reduction in thermal sensitivity has been verified in application within a fiber gyroscope using a PBGHCF[11].

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HCF also has several other benefits over traditional solid core fibers. Due to guiding light in an air core, the nonlinear coefficients are extremely low, making them suitable for high power applications[12]. Also, the propagation speed is close to the speed of light, decreasing latency of data transmission rates[13]. Additionally, the absorption of silica is greatly reduced, allowing transmission of mid-infrared light[14,15]. Finally, the hollow core leads to a much higher radiation insensitivity than standard optical fiber[16].

2. THEORY

Anti-resonant hollow core fibers (ARHCF) are quickly gaining attention for their excellent guiding properties, such as low loss and wide transmission windows[5]. ARHCF has much wider bandwidth, and simpler fabrication than PBGHCF. Additionally, even less of the core light overlaps with the glass structure of the fiber, potentially lowering the thermal sensitivity from the refractive index change even further than PBGHCF.

Various ARHCF designs have been investigated in both simulation and experiment in an attempt to reduce the overall attenuation and bend-induced losses as well as to shift the resonance wavelengths and provide customized ranges of high transmission [2–4,6,17,18].

ARHCFs achieve low propagation losses due to the strong suppression of coupling between the core modes and cladding modes[5]. Only around specific resonance wavelengths, strong coupling to outside modes leads to significant propagation losses of the core modes. These wavelengths are determined by the thickness of the silica boundaries, shown in Eqn. 1:

$$\lambda_m = \frac{2t}{m}\sqrt{n^2 - 1} \tag{1}$$

where λ_m is the resonance wavelength, t is the silica thickness, m is the order of the resonance, and n is the index of refraction of the silica. Figure 1 shows a scanning electron microscope (SEM) image of the ARHCF used in the following experiment. It consists of eight non-touching rings, each about 16 µm in diameter with a thickness of 300 nm, and an air core with a diameter of 34 µm. The outer diameter of the fiber is 135 µm, which allows it to be directly spliced with standard optical fibers.

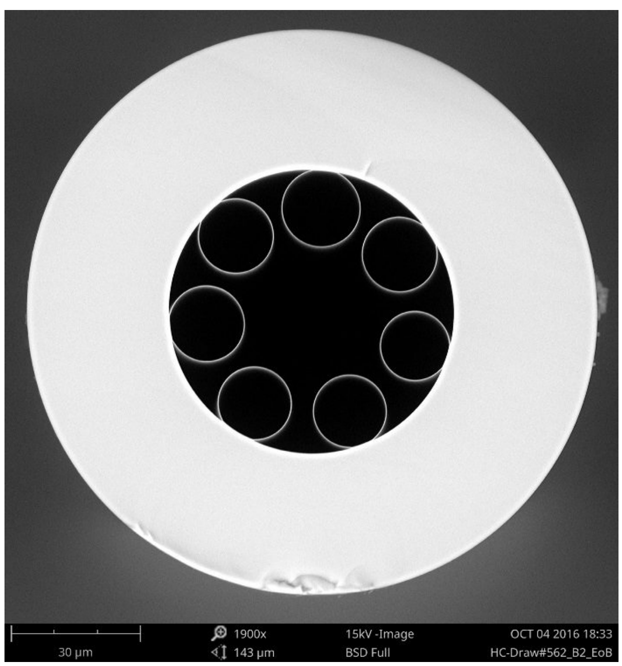

Fig. 1. SEM image of the facet of the ARHCF used in this experiment.

The ARHCF shown above was simulated in COMSOL Multiphysics. The fundamental mode at 1550 nm is shown in Fig. 2, showing very little overlap of the fundamental mode light with the silica glass structure. The loss of this mode was calculated to be 85 dB/km. While the large cores of ARHCF support higher order modes, they generally have much higher propagation losses than the fundamental mode, and are therefore lost after relatively short transmission lengths[19]. For this fiber, the losses of the higher order modes were calculated to be LP_{11}: 1 dB/m, LP_{21}: 20 dB/m, and LP_{02}: 170 dB/m. With imperfect launching conditions, some LP_{11} may be excited and still be present after 3.5 m, but for this experiment we are assuming that this fiber is approximately single mode. The loss ratio between the fundamental modes and the higher order modes can be optimized through the design of the structure in order to obtain the mode purity required for a given application[20].

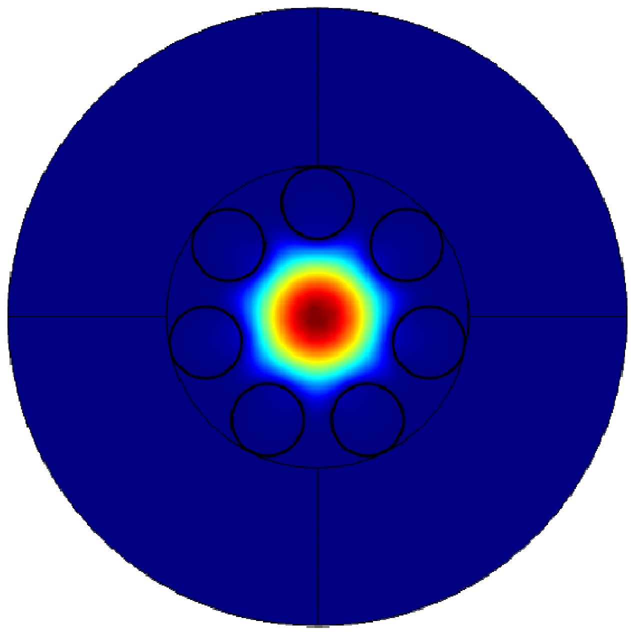

Fig. 2. Simulated fundamental mode of ARHCF from COMSOL Multiphysics, showing very little overlap of the light with the glass structure.

The transmission spectrum of this ARHCF was also simulated and is shown in Fig. 3. Due to the thickness of the rings, the first resonance is located at 600 nm, according to Eqn. 1. There are no resonances located above this wavelength, leading to a very wide usable bandwidth that would be well-suited to many applications. For this test, we are working in the 1550 nm region, which is well within the low loss region.

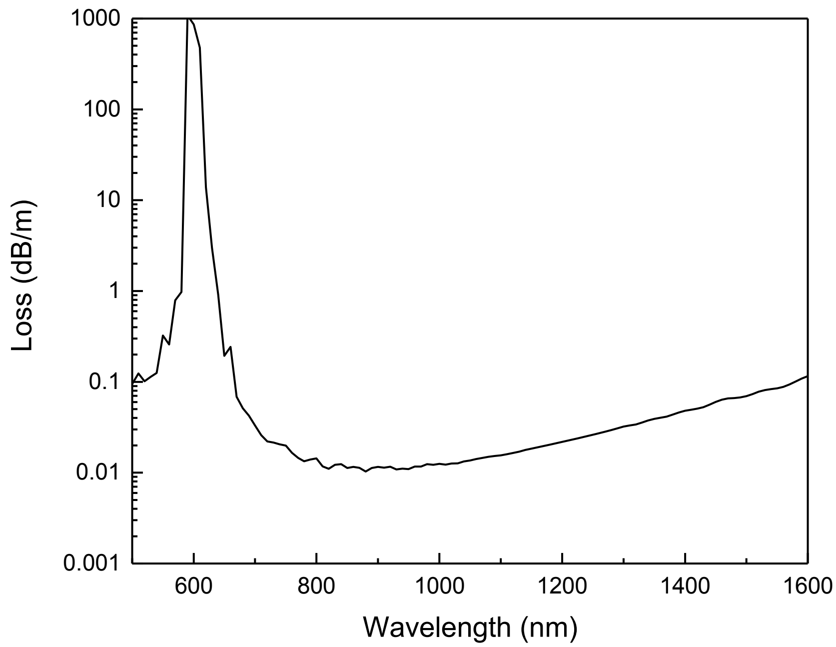

Fig. 3. Simulated transmission spectrum of the ARHCF, showing a resonance at 600 nm and low loss over a large bandwidth of wavelengths.

3. EXPERIMENT

In order to test the thermal sensitivity of the ARHCF, two all-fiber Mach-Zehnder interferometers were setup, and are shown in Fig. 4. The light source used was a narrowband laser operating around 1550 nm, and was split using a 50/50 fiber coupler in order to be able to monitor both interferometers simultaneously. One interferometer had 3.5 m of ARHCF spliced into one arm, and the other had 2.4 m of SMF spliced into one arm. These lengths were chosen so that the propagation lengths of the fibers were equal when factoring in the effective indices of refraction. The second arm of both interferometers contained only a short length of SMF coming from the 50/50 couplers. After the recombination of the interferometer arms again using fiber couplers, the signals were sent to two detectors connected to an oscilloscope. The portion of the interferometers containing the extra lengths of ARHCF and SMF from the first arm, as well as the short lengths of SMF of the second arm, were placed in an oven, with all 50/50 couplers outside of the chamber.

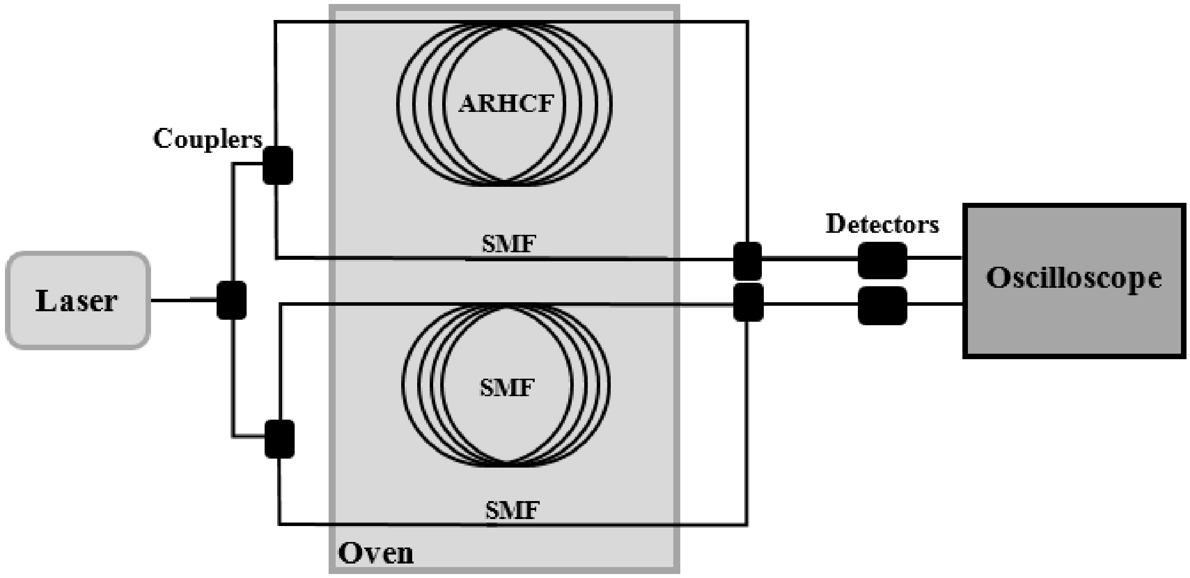

Fig. 4. Schematic of interferometer testing setup.

The oven was raised to a temperature of 50°C and held until stable. The oven door was then opened in order to quickly cool the chamber, as the signal from the detectors was monitored on the oscilloscope. An example plot of the interferometer signals is shown in Fig. 5. Clearly, the SMF output has a significantly faster delay change with temperature than the ARHCF. From this plot, the calculated improvement in temperature sensitivity gained through using the ARHCF is approximately a factor of 4. This agrees with the values measured by Dangui et. al which ranged from 3.6 to 5.3 depending on the PBGHCF[10].

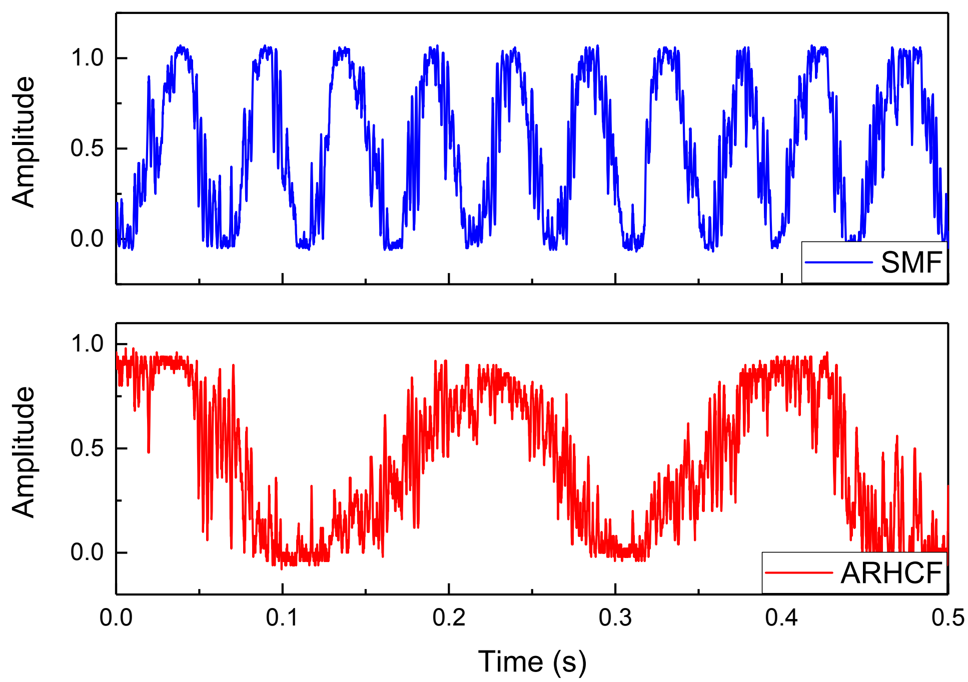

Fig. 5. Measured interferometer outputs of the SMF and ARHCF while the oven temperature decreased.

4. CONCLUSION

We have proposed the use of ARHCF for high precision timing applications, due to its lowered temperature sensitivity from standard SMF. While this has been proven with other types of hollow core fiber, we believe this is the first proof of concept for using anti-resonant hollow core fiber for increased temperature stability. Due to its simpler structure, and therefore less expensive fabrication, as well as its extremely large available bandwidth, the ARHCF may be preferable to PBGHCF for applications requiring high levels of temperature stability. Further work needs to be done in order to more robustly quantify the improvement factor, as well as to optimize the ARHCF structure design in order to decrease the thermal sensitivity as much as possible. It has recently been shown that through careful design, the thermal sensitivity of PBGHCF can be reduced to almost zero[21]. A similar expansion coefficient cancelling design may also be possible for ARHCF.

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