Evanescent field refractometry in planar optical fiber


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This work demonstrates a refractometer in Integrated Optical Fiber (IOF), a new optical platform that planarizes fiber using flame hydrolysis deposition (FHD). The unique advantage of the technology is survivability in harsh environments. The platform is mechanically robust, can survive elevated temperatures approaching 1000°C and exposure to common solvents, including acetone, gasoline and methanol. For the demonstrated refractometer, fabrication was achieved through wet etching an SMF-28 fiber to a diameter of 8 µm before FHD planarization. External refractive index was monitored using fiber Bragg gratings, written into the core of the planarized fiber. A direct refractive index was made to an alternative fiber Bragg grating refractometers is made. For which the developed platform is shown to have comparable sensitivity, with the added advantage of survivability in harsh environments.

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Optical monitoring in environmental extremes is an important research area, as it can provide parameter information that would otherwise be difficult to access electronically. Sensors based on optical fiber in particular have proven to be attractive [1,2] namely as they do not pose a spark risk in flammable environments, have immunity to electromagnetic interference, are resilient at elevated temperatures (over 100°C) and have the ability to form part of a large distributed network. This work reports upon a new passive planar optical platform termed Integrated Optical Fiber (IOF). Its key advantage is the ability for it to be deployed in even harsher environmental conditions. It possesses the optical advantages associated with fiber, whilst enabling a basis for planar functionality. The IOF platform, illustrated in Figure 1, is composed of an optical fiber bound to a planar substrate through use of Flame Hydrolysis Deposition (FHD). The FHD glass forms a miscible alloy between the planar carrier substrate (silicon) and the fiber during a high temperature (>1000°C) consolidation phase. There is no use of glues or epoxy. As such the platform can be taken up to elevated temperatures approaching that used in its consolidation. It can also endure exposure to common solvents (e.g. acetone, methanol and gasoline) with no notable degradation. As FHD glass is of optical quality it is also suitable for direct optical interaction. Furthermore optical fiber can transition on and off chip, as illustrated in Figure 1 (b). This monolithic coupling feature further removes the requirement for glues and epoxy that are typically used to secure an optical fiber, when coupling to a planar chip [3]. Thus the mechanical weakness brought about by these mechanisms of binding are also removed.

![Image](http://dx.doi.org/10.1364/OL.99.099999)

**Fig. 1.** (a) Cross-sectional profile of an Integrated Optical Fiber and (b) demonstration of off-chip / on-chip routing (for scale, optical fiber shown is unetched SMF-28 with 125 µm diameter).

Developments in IOF have thus far been limited to utilizing the environmental stability [4] and/or physical robustness [5,6] of the platform. This work is the first to report direct optical interaction between the fiber core and the FHD binding medium. In this demonstration the evanescent field of the planarized fiber is exposed and a Bragg grating used to infer external refractive index. It is noted the Bragg wavelength, λ, is dependent upon the effective refractive index, neff, relating to the periodicity of the grating, A,

$$\lambda = 2\Lambda n_{eff}$$

(1)

Fiber Bragg gratings have the distinct advantage of multi-parameter multiplexed sensing capability [7], which include the ability to monitor temperature, strain and external refractive index [8].

Work by this group has previously commercialized planar-Bragg grating refractometers, for biopharma applications [9,10], achieving spectral sensitives of 190 nm/RIU (RIU, refractive index units) and corresponding index resolutions of 2x10^{-6} RIU [3]. Other notable refractometer configurations include those that harness Surface Plasmon Resonances [11] and those that utilize microstructured fiber [12-14]. These typically have an order of magnitude increased
RIU resolution, but do not have the multiplexing capability associated with fiber Bragg gratings (FBGs). There are also several reported approaches that expose the evanescent field of an optical fiber and interrogate with long or short period gratings. These approaches couple light from a guided core to cladding modes through use of tapers [15], tilted Bragg gratings [16–18] long period gratings [19] and utilize surface plasmon interactions to enhance sensitivity [1,12,20]. Due to bandwidth efficiency (and so the potential for greater parameter monitoring) this work considers guided core mode confinement only. For this, two principle geometries exist, side access [8,21] and uniform access [22] illustrated in Figure 2. Side access, is achieved by potting the fiber into an epoxy and machining it, via lapping and polishing. Uniform access, uses an etchant, typically buffered Hydrofluoric acid, to uniformly wet etch the silica-clad material. Whilst both these approaches have been proven, they have limitations when exposed to certain environments including certain common solvents, turbulent flows or high temperatures (in excess 300°C). Upon exposure to these environments they exhibit an inherent fragility.

This work builds largely on the concept of thinned fiber Bragg gratings (thFBGs) [15,22], which is a uniform access geometry. It is argued that as a greater proportion of the evanescent field can be exposed an enhanced sensitivity to external refractive index can be attained, compared to a side access approach of a comparable effective fiber diameter, d. However, as a result of the fibers small diameter (< 10 µm), the geometry is mechanically more fragile, e.g. to turbulent flows. This work planarizes and ruggedizes the thFBG concept, with minimal compromise to sensitivity using an IOF geometry, illustrated in Figure 2.

![Image](https://example.com/image1)

**Figure 2.** Cross-sections of the evanescent field exposed core in a uniform access, side access and IOF layer-up geometry respectively.

Design considerations for thinned IOF need to ensure that waveguiding is still maintained. As such a 15 µm oxide layer is required between the fiber and silicon, as shown in Figure 2. The purpose of the oxide is to act as an optical buffer, so light does not leak into the underlying silicon substrate. Another design consideration is the refractive index and thickness of the FHD layer. This must be tailored such that light does not couple out from the core into the features immediately beneath the fiber that resemble a frozen-in meniscus, termed and labeled in Figure 2 as wings. To understand how fabrication variables influence sensitivity, a commercial mode solver (FIMMWAVE by Photon Design) was used. In these computer simulations the diameter of fiber is set to 9 µm, the core diameter to 8 µm and the cross-sectional area of wings as 3 µm². The first parameter considered was wing refractive index contrast, Δn, defined relative to the thermally grown oxide (assumed to be 1.4452 at 1550 nm wavelength). Figure 3 shows the simulated sensitivity for this parameter around an external refractive index of 1.444, a refractive index region of particular interest for automobile and aviation fuel monitoring [23]. It is evident from this simulation that the lower the refractive index of the wings the greater the spectral sensitivity. This response is understood through modal confinement. As the refractive index of the wings increase, an increasing fraction of the modal power is supported in and near their proximity, reducing external fractional power and thus sensitivity. Modal confinement is illustrated in the inserts of Figure 3, for the two extremities of the simulation.

![Image](https://example.com/image2)

**Figure 3.** Finite Element Method simulation considering the sensitivity dependence subject to the refractive index of the IOF wings (highlighted in yellow within the insert) around an external refractive index of 1.444. Modal power distribution is shown in inserts.

The refractive index of the fiber core was also considered in the simulations. This parameter can be manipulated through UV exposure, feasibly this can be of the order 2x10⁻⁵. Figure 4 shows the response to this parameter. As the refractive index of the core increases, as the inserted modal solutions depict increased modal confinement in the core occurs for high core refractive indices, thus reducing sensitivity.

![Image](https://example.com/image3)

**Figure 4.** Finite Element Method simulation considering the sensitivity dependence subject to the refractive index of the core (highlighted in yellow within the insert) around an external refractive index of 1.444. Modal power distribution is shown in inserts.
To test the theoretical models a demonstrator was fabricated and calibrated using Cargille refractive index oils (Cargille Labs, series AAA and AA). Fabrication involved mechanically stripping the acrylate coating from SMF-28 optical fiber, before wet etching it in buffered HF solution (29% concentrated). Etching was periodically monitored using an optical microscope and an etch rate of 0.53 μm/min was inferred. At a diameter of 8 µm the wet etch was ceased and the fiber was layered onto a silicon wafer, with a 15 µm pre-grown oxide. To form IOF an adapted FHD process was used [5]. The deposition passed chloride based pre-cursors of SiCl₄ at 137 sccm, PCl₅ at 31 sccm and BCl₃ at 69 sccm through an argon sheathed oxy-hydrogen flame with flow rates of 5.0 L/min, 6.5 L/min and 1.9 L/min for Ar, H₂ and O₂ respectively. The FHD coating was subsequently consolidated at a temperature of 1150°C in a Helium flow atmosphere of 1.90 L/min. Through Scanning Electron Microscopy (SEM) imagining the cross section of the fiber was estimated to have an FHD infill below the fiber (wings) of 3 µm², shown in Figure 5 insert. The Borophosphosilicate deposited glass had a measured refractive index comparable to that of the thermally grown oxide (1.4452 ± 0.0001 at 1553 nm wavelength) calibrated using a prism coupler technique (Metricon). The nominal thickness of the deposited FHD layer was 0.5 µm. This was characteristic thicker for the wing features as a meniscus forms during the consolidation phase.

Surface roughness of the optical fiber was measured using a white light interferometer (ZeScope, Zemetrics). Immediately after HF etching fiber roughness was measured to be 62.2 nm (Sa) and after FHD processing this was reduced to only 9.1 nm (Sa). From analytical theory, it is understood that propagation loss scales to the square-root of surface roughness [24]. It is therefore expected that a reduction in propagation loss will follow FHD processing. Quantification of this is considered beyond the scope of this report but will be the subject of future investigation.

For external refractive indices around 1.435, the simulated spectral sensitivity is 32 nm/RIU. To compare this level of sensitivity with the other geometrical approaches outlined in Figure 2, empirical data was extracted from the literature [22,25] and simulations made, illustrated in Figure 6. The simulated spectral sensitivities for the fully etched (thFBG) and attached fiber (IOF) geometry is comparable to empirical data. The simulated sensitivity for the side access (buried FBG) regime underestimates sensitivity. However, this is believed to be due to the additional enhancement to the evanescent field brought about through the curved nature of the fiber when it is potted. From Figure 6 it is observed that the spectral sensitivity of IOF sits between the side access and uniform access configurations. Practically it was not possible to acquire sensitivities over 1.436 as degradation of the spectral feature made interpretation difficult. This is believed to be a consequence of...
alignment issues of the Bragg grating, previously discussed. A misaligned grating would have variable average core refractive index, which as observed in Figure 4 has a large influence on sensitivity. Thus at higher external refractive indices the grating quality deteriorates. Practically, this could be overcome through improving alignments or moving to alternative FBG writing approaches that do not use a small writing spot. As previously noted the effective refractive index in air for the device is 1.45698. Furthermore, the FHD and thermal oxide both have indices of 1.4452. Therefore, guiding would still be expected at external refractive indices approaching 1.45. Through simulations it can be inferred that sensitives in this region would approach 224 nm/RIU.

It is understood that thermal cross sensitivity is a limiting factor for the device's current design. Whilst this is minimal in a temperature-controlled laboratory, it would evidently become an issue in practical applications. There are several approaches for thermal referencing, the simplest being use of a thermal reference grating that is locally placed and has sufficient FHD coverage region of particular interest for automobile and aviation gasoline monitoring [23] as to be independent of external refractive index [10]. The implementation of this would require either localized etching along the fiber or localized FHD burial.

Quantification for the robustness of such a platform has no mechanical standard to draw. Robustness was therefore measured through an attempted dislodgement of the fiber with a fingernail. In this qualification the fingernail was passed firmly against the side of the fiber. Five attempted dislodgments were made after the fiber was subject to a 48 hours soak in acetone, gasoline and methanol respectively and a 300°C bake in air for 48 hour (erasure of Direct UV written Bragg gratings is known to occur at 400°C). After these tests there was no notable physical degradation of the fiber or the optical signal, the fiber remained secured to the planar substrate. It is noted that recent progress in thermally regenerated Bragg gratings may offer an extension to the thermal range of FBG's in this layered configuration [26].

In conclusion the first demonstration of an IOF refractometer has been made. This additionally marks the first demonstration of an IOF with exposed evanescent field. Building upon this the consideration of optical interaction between separate attached fibers to create, for example, directional and cross coupler components can be built upon, a concept that could achieve ultra-low loss integrated optics.

IOF was observed to have similar sensitivity compared to alternative geometries, but with the added advantage of being tolerant to environmental extremes. Future work shall consider specific harsh environmental deployments for the platform.

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References