

Fabrication and Characterization of a Sapphire Fabry–Pérot Fiber Sensor for High-Temperature Measurement up to 1000 °C

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Summary

We present the fabrication and characterization of a sapphire-based Fabry–Pérot interferometric sensor produced by optimized filament splicing, demonstrating a compact and reliable device capable of accurate and robust temperature measurement up to 1000 °C.

Keywords: High-temperature sensing, Sapphire fiber, Fabry–Pérot interferometer, Optical fiber sensor, Interferometric sensing

Introduction

Fiber-optic sensors are widely used for high-temperature monitoring due to their compact size, electromagnetic interference (EMI) immunity, and wavelength encoding. These features make them highly suitable for harsh environments such as aircraft engines, energy systems, and industrial processes [1–3]. However, high-temperature fiber sensors in conventional silica fibers, including regenerated Fiber Bragg Gratings (RFBGs), Type-I, and Type-II sensors, exhibit signal drift or degradation above 700 °C due to structural relaxation and viscoelastic behavior of silica [4,5]. This limits their stability and long-term reliability in extreme conditions. To overcome this, sapphire fibers (SF), with melting point above 2000 °C, can serve as a stable high-temperature sensing element due to their excellent thermal robustness, chemical stability, and wide optical transparency window [6,7]. At the same time, in our approach, standard silica fibers continue to provide efficient light guidance and compatibility with interrogation systems, enabling a hybrid sensing configuration.

Existing sapphire-based sensors such as multimode FBGs and extrinsic Fabry–Pérot interferometers (FPIs) often require complex designs, precise alignment, or femtosecond laser processing, which limits their practicality and scalability [8–13]. To offer a more practical solution, we implement a sapphire fiber based Fabry–Pérot interferometer (SFPI) formed by splicing a short sapphire fiber piece (~2 mm) onto a standard single-mode fiber (SMF), thereby creating a compact intrinsic

interferometric cavity defined by the silica–sapphire interface and the sapphire–air end-face. This configuration enables wavelength-encoded sensing based on interference between reflected signals. In this study, we present the detailed fabrication procedure and complete characterization of the SFPI, demonstrating stable temperature measurement up to 1000 °C with good fringe visibility, repeatability, and calibration performance.

Working principle and FPI theory

A commercially available single-mode interrogator (SM125, Micron Optics, USA) was used for signal generation and detection in reflection mode; thus, only a single delivery fiber was required. The optical signal propagates through the standard silica fiber (refractive index $n_1 = 1.4478$) toward the silica–sapphire interface, where a partial Fresnel reflection ($R_1 = 0.87\%$) occurs due to the refractive index mismatch between silica and sapphire ($n_2 = 1.7464$). The remaining optical power is transmitted into the sapphire fiber, where it propagates and undergoes a second partial reflection at the sapphire–air interface ($n_0 = 1$), with reflectivity $R_2 = 7.39\%$. These two reflecting interfaces form a low-finesse intrinsic Fabry–Pérot interferometer (SFPI) with cavity length $L \approx 2.2 \text{ mm}$ (see Fig. 1).

Due to the relatively low reflectivities ($R_1 \ll 1\%$ and $R_2 < 10\%$), the cavity operates in the low-finesse regime, where multiple internal reflections can be neglected and the interference can be described using a two-beam interference model.

The resulting interference intensity is given by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos\left(\frac{2\pi}{\lambda} \text{OPD}(T) + \phi_0\right), \quad (1)$$

where I_1 and I_2 correspond to the reflected intensities associated with R_1 and R_2 , respectively. The interference term contains the phase component, which is governed by the optical path difference (OPD) of the cavity

$$\text{OPD}(T) = 2n(T)L(T), \quad (2)$$

which depends on both the temperature-dependent refractive index $n(T)$ (thermo-optic effect) and the thermally induced expansion of the cavity length $L(T)$. Constructive interference (resonance condition) occurs when,

$$2n(T)L(T) = m\lambda, \quad (3)$$

where m is the interference order. Variations in temperature modify both $n(T)$ and $L(T)$, resulting in a shift of the resonant wavelengths (fringe positions). By tracking this wavelength shift, the temperature can be determined.

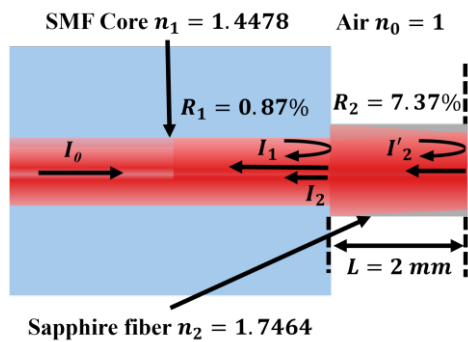


Fig. 1: SFPI schematic with Fresnel reflections (R_1 , R_2), refractive indices (n_1 , n_2 , n_0), and cavity length L .

Fabrication of SFPI

The SFPI sensor fabrication begins with the preparation of a standard single-mode fiber (SMF) and a single-crystal sapphire fiber (SF). The SMF was first stripped of its protective coating and then cleaved using a precision cleaver to obtain a flat and perpendicular end-face (Fig. 2A), ensuring efficient optical coupling at the splice interface.

The sapphire fiber was initially available as a longer segment with a rough and irregular end-face (Fig. 2B), along with its side profile as shown in Fig. 2C. Due to its anisotropic crystal structure and high mechanical hardness, the sapphire fiber cannot be cleaved reliably. Therefore, the end-face was mechanically polished using progressively finer abrasive films (6 μm to 1 μm) to achieve a smooth and optically flat and perpendicular surface (Fig.

2E), which is essential for controlled reflection at the sapphire–air interface.

Following end-face preparation, both fibers were positioned for splicing with careful core-to-core alignment and a controlled pre-gap (Fig. 2D). This pre-gap is critical to prevent unwanted physical contact during the heating phase, accounting for thermal elongation of the sapphire fiber (~24 μm observed at 52 W filament power). Since direct temperature control is not available in the filament splicer, the splice parameters were empirically optimized to compensate for thermal expansion during the heating stage and subsequent contraction upon cooling, ensuring stable interface formation.

The fibers were then fused using a filament-based fusion splicing system (LSF4000, Vytran, UK), where controlled heating softens the silica while maintaining the structural integrity of the sapphire. The final splice region (Fig. 1F) exhibits a mechanically robust joint with precise core alignment, forming a stable optical interface suitable for interferometric operation.

After splicing, the sapphire fiber was intentionally shortened by controlled breaking at approximately 2–3 mm from the splice point to define the cavity length. The newly created sapphire end-face was again polished using the same procedure, resulting in two well-defined, parallel reflecting surfaces forming the intrinsic Fabry–Pérot cavity. This sequence ensures reproducible SFPI fabrication with controlled geometry and reliable optical performance.

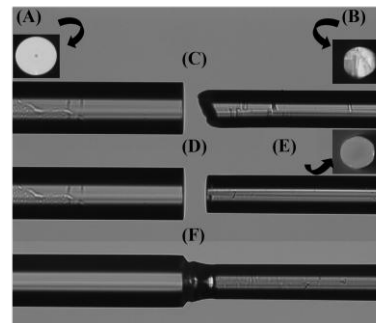


Fig. 2: SFPI fabrication: (A) SMF cleaved end-face, (B) unpolished SF end-face, (C) alignment, (E) polished SF, (D) pre-splice positioning, (F) final splice

Following the splice formation, the reflected signal evolves with cavity formation and end-face quality. For a long sapphire fiber (~30 cm), no interference is observed and the signal remains nearly constant (Fig. 4A), due to weak back-coupling and multimode propagation. After trimming to ~2.5 mm, partial modulation

appears (Fig. 4B), but fringe visibility remains low due to the unpolished sapphire–air interface causing scattering and reduced reflectivity. After polishing the second end-face, a stable Fabry–Pérot interference pattern with high visibility ($\sim 55\%$) is obtained (Fig. 4C), confirming the formation of a well-defined two-beam cavity.

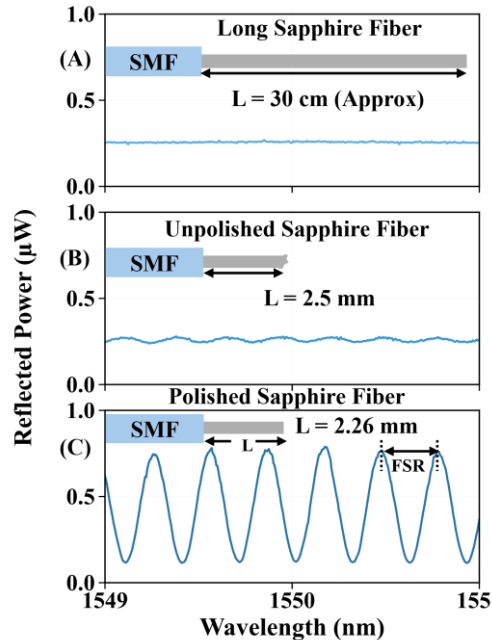


Fig. 4: Reflected signal evolution after splice: (A) long SF (no interference), (B) trimmed unpolished SF (low visibility), (C) polished SFPI (~ 2.26 mm) with strong-visibility of Fabry–Pérot fringes ($FSR \approx 0.304$ nm)

The measured spectra confirm this behavior, and the free spectral range ($FSR \approx 0.304$ nm) validates the cavity length using Eq. (4),

$$L = \frac{\lambda^2}{2n_2 \cdot FSR} \approx 2.26. \quad (4)$$

After obtaining a stable high-visibility SFPI signal and a well-defined cavity structure, the sensor was encapsulated in a capillary for mechanical protection and environmental isolation, making it ready for high-temperature testing and calibration.

High-temperature measurements:

After fabrication, the sensor was placed inside a calibration furnace (Pegasus Plus 1200S, Isothermal Technology Ltd., UK) together with a Type-R thermocouple, as shown schematically in Fig. 3. The SFPI and thermocouple were positioned in close proximity to ensure identical thermal conditions. The reflected spectra were recorded using an optical interrogator (1510–1590 nm, 5 pm resolution) at a sampling rate of

1 Hz. An in-house LabVIEW program processed each spectrum in real time by fitting a second-order polynomial to the upper 50% of the tracked fringe peak, enabling wavelength tracking.

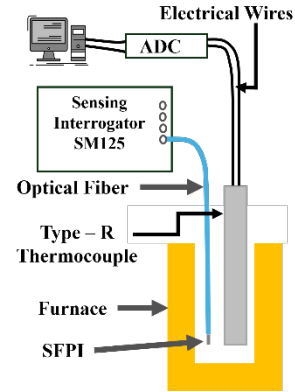


Fig. 3: Schematic of the high-temperature calibration setup showing the SFPI sensor and Type-R thermocouple co-located inside a furnace, with optical interrogation via a broadband interrogator.

The measured oven temperature and the tracked fringe wavelength are presented in Fig. 5, where the left y-axis corresponds to oven temperature (set and measured), and the right y-axis corresponds to the fringe wavelength. The temperature profile consisted of stepwise heating from room temperature (~ 20 °C) to 1000 °C followed by cooling, with a dwell time of 2 h at each step to ensure thermal equilibrium. The tracked fringe wavelength follows the thermocouple temperature closely over the entire cycle, demonstrating stable operation of the SFPI. Over this range, the

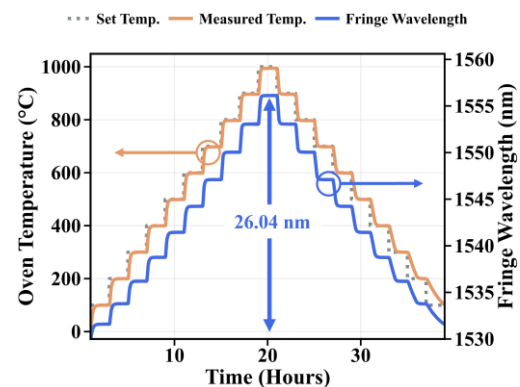


Fig. 5: Set and Measured temperature steps (left y-axis) and corresponding fringe wavelength response (right y-axis); the tracked fringe follows the measured temperature steps, showing a total wavelength shift of ~ 26.04 nm.

selected fringe exhibits a total wavelength shift of approximately 26.04 nm, corresponding to a temperature change from ~21 °C to ~994 °C.

The calibration curve is shown in Fig. 6, where the fringe shift $\Delta\lambda(T)$, referenced to the wavelength at 200 °C ($\lambda_{ref} = 1533.785$), is plotted as a function of temperature. The fringe shift values were obtained from steady-state averages over a 10 min window near the end of each dwell period. A fifth-order polynomial was fitted to the combined heating and cooling dataset, yielding an excellent agreement. The residuals remain below ± 0.02 nm across the full temperature range, confirming strong consistency between heating and cooling branches and negligible hysteresis.

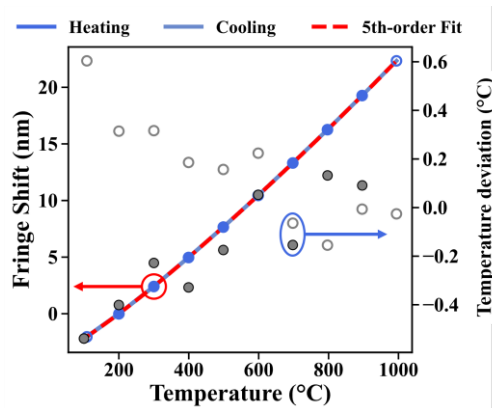


Fig. 6: Fringe shift versus temperature referenced to 200 °C; heating (filled) and cooling (hollow) data with a fifth-order polynomial fit (dashed, red). Left y-axis: fringe shift (nm); right y-axis: temperature deviation (°C), remain within ± 0.6 °C.

The fitted response exhibits a nonlinear increase in sensitivity with temperature. The sensitivity rises from approximately 23.18 pm/°C at 200 °C to 31.63 pm/°C at 1000 °C, reflecting the combined temperature dependence of the thermo-optic coefficient and thermal expansion of sapphire.

Using the polynomial calibration fit parameters, the temperature was reconstructed from the measured fringe wavelength. The temperature deviation between the SFPI-reconstructed temperature and the measured thermocouple temperature,

$$\text{Temperature Deviation} = T_{SFPI} - T_{TC}, \quad (5)$$

is shown in Fig. 6 (right y-axis). The resulting temperature deviation remains within ± 0.6 °C over the full range. These results demonstrate high repeatability of the SFPI sensor over the investigated temperature range.

Summary

An intrinsic sapphire fiber Fabry–Perot interferometer (SFPI) was demonstrated for high-temperature sensing up to 1000 °C. The sensor exhibits a wavelength shift of ~26.04 nm and a high sensitivity reaching 31.6 pm/°C at 1000 °C. The reconstructed temperature shows excellent agreement with a reference Type-R thermocouple, with a maximum deviation below 0.6 °C, confirming stable operation over the full range.

The proposed approach enables efficient light guidance using a standard silica single-mode fiber (SMF) integrated with a compact sapphire sensing element (~2.2 mm), allowing the use of a simple, commercially available interrogation system. The silica–sapphire splice remains mechanically robust and optically stable under high-temperature conditions, demonstrating reliable sensor integrity. Compared to regenerated Fiber Bragg Gratings (RFBGs), the SFPI exhibits significantly higher sensitivity, highlighting the advantage of interferometric sensing [4]. Overall, the sensor offers a compact, fabrication-efficient, and high-performance solution for harsh-environment temperature sensing.

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