

Advancing Optical Sensing Through Tapered Optical Fiber and Tilted Fiber Bragg Gratings: Fundamentals, Trends, And Hybrid Possibilities

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Keywords

*Tilted fiber Bragg grating
TFBG sensor*

Article History

Received: 25 May 2025

Accepted: 10 June 2025

Published: 30 November 2025

Abstract

A label-free optical biosensor presents an innovative solution for biochemical detection, besides tapered optical fiber (TOF), Tilted fiber Bragg gratings (TFBGs) have been shown to have distinctive properties that enable the creation of highly precise sensors, especially in biochemical realm, while maintaining cost efficiency in both manufacturing and signal interrogation. This review compares both the TFBGs and TOF, Emphasizing the latest developments in their fabrication techniques, sensing mechanisms, and limitations. Most recent achievements of both will be discussed through examples from the literature. Pros and cons will be assessed and discuss the potential advantages of combining both structures.

1. Introduction

Fiber Bragg Grating (FBG) sensors are valued for their compactness, multiplexing capabilities, and immunity to electromagnetic interference. Enhancements in sensitivity have led to the development of Tilted FBGs (TFBGs), which enable strong cladding mode coupling for precise refractive index (RI) detection, particularly with plasmonic coatings. Meanwhile, tapered fiber-based biosensors have gained attention for their high RI sensitivity, utilizing biconical tapering to enhance evanescent field penetration. When combined with localized surface plasmon resonance (LSPR), tapered fibers significantly amplify interactions with the surrounding medium, enabling label-free biosensing. This review compares recent advances in TFBGs and tapered fiber biosensors, examining fabrication techniques, sensing mechanisms, and integration challenges for improved biosensing applications.

2. Advanced Fabrication Techniques:

2.1. Tilted Fiber Bragg Gratings (TFBGs)

Recent advancements favor femtosecond laser (FSL) fabrication over traditional UV laser methods [1], eliminating hydrogen loading and annealing complexities. FSL enables small angle tilted FBGs with precise control of grating period and mechanical integrity. Early phase-mask techniques limited flexibility, but direct-writing methods including Point-by-Point (P-b-P) [2], Line-by-Line (L-b-L), and Plane-by-Plane (Pl-b-Pl) have emerged, enhancing structural robustness and tailoring

grating angles [3], [4], [5]. P-b-P suffered uneven RI modulation, causing insertion loss, now addressed by L-b-L and Pl-b-Pl. Utilizing an angle-adjustable mechanical setup with an optical slit between 50-fs FSL and objective lens, wavefront shaping is optimized for fiber tapering. TFBGs exhibit high cladding mode intensities and minimal insertion loss, making them highly effective for precision sensing applications.

2.2. Tapered fiber (TOF)

The tapered optical fiber (TOF) structure is designed to enhance evanescent field interaction, allowing guided light to penetrate the surrounding medium for high-sensitivity sensing. TOF fabrication has progressed from flame heating and arc discharge [6], which lacked precision, to chemical etching, enabling selective cladding removal for better optical interaction. The latest laser-based processing, particularly CO₂ and femtosecond lasers, has transformed TOF technology by achieving intricate taper geometries with high repeatability, optimizing sensitivity and signal transmission [7]. These advancements have expanded TOF applications, making them highly effective for biosensing, chemical detection, and environmental monitoring.

3. Sensing Mechanisms of TFBG and Tapered Fiber Biosensors

Tilted Fiber Bragg Gratings (TFBGs) couple core-guided light into backward-propagating cladding modes, making them highly sensitive to surrounding refractive index (SRI) changes. When coated with metals like gold, they enable surface plasmon resonance (SPR), where shifts in RI cause a red shift (longer wavelengths) or blue shift (shorter wavelengths). Variations in coupling efficiency modify dip depth and amplitude, allowing precise molecular detection.

In contrast, tapered optical fiber (TOF) sensors enhance evanescent field interactions, improving light penetration for high-sensitivity sensing. TOFs utilize evanescent wave absorption and SPR, often integrating advanced coatings like graphene oxide and gold nanoparticles for better signal enhancement. These mechanisms make TFBGs and TOFs vital for biosensing applications such as cancer biomarker detection, protein analysis, and environmental monitoring.

4. Sensor Architecture, AI Integration, and Evolving Trends

Table 1 summarize the key advances of the sensor architecture based of TFBG and tapered fibre sensors.



Table 1: Summary of key architectural advances of each sensor type

Sensor Type	Key Architectural Advances	Representative Study & Findings
TFBG	Multilayer coatings (gold encapsulation, graphene oxide) enhance sensitivity and spectral resolution.	Prathap & Saara in [8] introduced a gold-encapsulated TFBG for improved biomolecular trapping, achieving strong refractive index sensitivity for biosensing applications.
	Machine learning algorithms (PCA & polynomial regression) improve spectral data processing, reducing noise and increasing accuracy.	Chubchev et al. in [9] applied AI to process plasmonic TFBG spectral data, achieving ultra-high resolution (9×10^{-6} RIU) and improving sensor calibration across different experiments.
Tapered Fiber Sensors	Optimized taper geometry (waist diameter, length) and nanomaterial integration (e.g., ZnO, AuNPs) enhance evanescent field interaction and localized SPR (LSPR).	Borjikhani et al. [10] demonstrated a biconical tapered fiber coated with hollow Au nanoparticles for cancer biomarker detection, achieving 489.8 nm/RIU sensitivity.

5. Potential of Hybrid TFBG-Tapered Fiber Sensors

The idea of combining tilted fiber Bragg gratings (TFBGs) with tapered fiber architectures introduces a hypothetical pathway for improving optical biosensing performance. While this concept has not been experimentally validated, it presents key questions worth investigating:

Hypothesis for Potential Benefits

- Could the evanescent field enhancement of tapered fibers improve TFBG spectral sensitivity?
- Would localized TFBG resonance features allow for simpler spectral interpretation, reducing dependence on machine learning?
- Could a hybrid structure support multiparameter sensing, enabling detection of refractive index, polarization, and intensity shifts simultaneously?

Challenges & Uncertainties

- Fabricating a precisely controlled hybrid structure may require advanced inscription techniques, introducing complexity.
- Spectral noise and drift in tapered fibers could affect TFBG resonance clarity, requiring additional signal processing methods.
- If spectral responses remain highly nonlinear, AI-driven correction may still be necessary, limiting computational simplifications.

Since this concept has not been tested, future research should experimentally assess feasibility, optimize fabrication methods, and compare performance metrics against standalone TFBG and tapered fiber sensors. By systematically evaluating these factors, researchers can determine whether this hybrid approach truly reduces complexity or introduces new challenges.

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