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Enhanced fabrication process for *in situ* triboluminescent optical fiber sensor for multifunctional composites

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ABSTRACT

The *in situ* triboluminescent optical fiber (ITOF) sensor is a proprietary sensor developed by High-Performance Materials Institute researchers. The ITOF sensor consists of polymer optical fiber and manganese-doped zinc sulfide (ZnS:Mn) which has the highest triboluminescent (TL) emission capability among all inorganic crystals. An automated fabrication machine was designed to fabricate consistent ITOF sensor, i.e. uniform TL coating on optical fiber, by a continuous dip coating process. The consistency of the coating thickness depends on the stress distribution on the ITOF sensor, and the vertical alignment of the fiber during the coating process. Several batches of ITOF sensors with different thickness were fabricated by the automated coating machine. The average diameter of the ITOF sensor is approximately 1.51 mm and 1.45 mm for 30 wt% and 50 wt% crystals, respectively, at coating speed of 1.618 mm s^{-1}. The ITOF sensors were embedded into the glass fiber composites and tested under flexural loading to detect composite failure. Results showed that ITOF sensors can detect shear failure of the flexural beams, and the TL signals were impeccably aligned with the acoustic signals. The compact ITOF sensor fabrication machine can consistently, continuously produce ITOF sensors with almost zero waste.

1. Introduction

Triboluminescence is an optical phenomenon exhibited by solid materials when they are stressed or fractured [1–3]. The phenomenon was first mentioned by Sir Francis Bacon with sugar about 400 years ago as published in *The Advancement of Learning* [4–6]. Extensive research work has been done since the 20th century to employ this interesting phenomenon for various applications such as damage and structural health monitoring in engineering structures [2,3,7–10].

There are thousands of different triboluminescent (TL) materials including both organic and inorganic materials. Among all crystals, approximately 50% of inorganic crystals and 30% of organic crystals exhibit TL behavior [5]. Xu et al. [11] compared the TL intensity of various inorganic materials under identical mechanical stress conditions. The comparison clearly indicates that manganese-doped zinc sulfide (ZnS:Mn) is one of the brightest inorganic crystals, which means more light is emitted with fewer crystals as compared to other triboluminescent crystals. Therefore, ZnS:Mn has the most potential for TL-based sensor systems and is a great candidate material for *in situ* triboluminescent optical fiber (ITOF) sensors.

The ITOF sensor is an integrated sensing and signal transmission system that can be readily integrated into large civil and aerospace composite structures to provide *in situ*, distributed and real-time damage monitoring [8,12]. Therefore, the composite evolves into a multifunctional state in which the material system is intentionally engineered to exhibit sensing functionalities. Multi-functional composites have the ability to perform more than one principal function taking place at a time either sequentially or simultaneously. One primary function is to retain structural integrity, while other non-structural functions could be sensing, self-healing energy harvesting/storage or thermal conductivity [13–15]. As a sensing component, sensors such as fiber optics [16–18], smart piezoelectric films [19] or CNTs [20,21] are embedded in multifunctional composites. The ITOF sensor combines the highly desirable features of polymer optical fibers (POF) with the TL property of ZnS:Mn. The ITOF sensor, with the integrated sensing and transmission components, converts the energy from damage events like impacts and crack propagation into optical signals that indicate the damage magnitude. Fig. 1 shows a schematic of an ITOF sensor. Many research works have utilized ITOF sensors for structural health monitoring of composite and concrete structures [8,12,22–25] and damage monitoring of the adhesive bond of composite structures [26]. Olawale et al. [27] demonstrated the ITOF sensor's real-time and distributed

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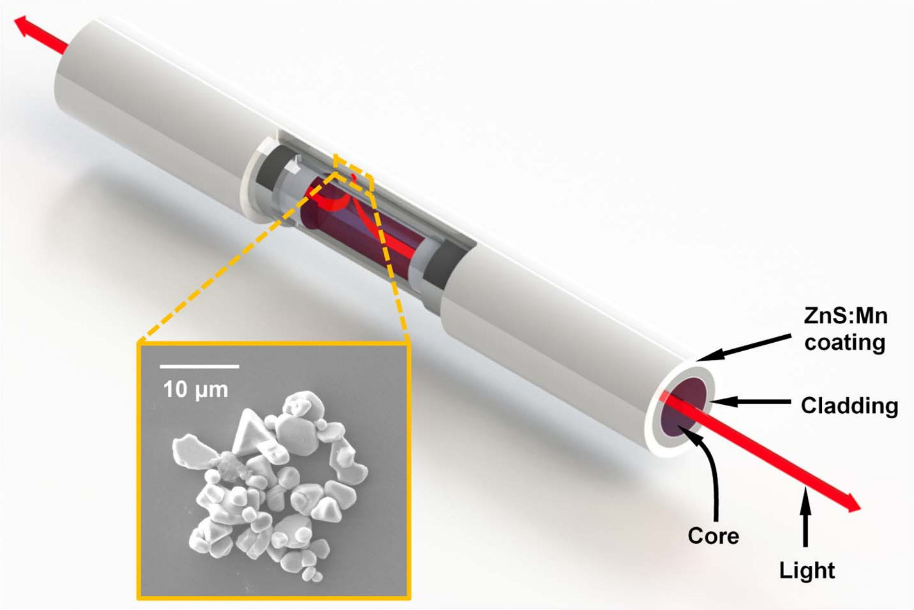

Fig. 1. Illustration of the ITOF sensor. The inset shows the SEM micrograph of ZnS:Mn crystals.

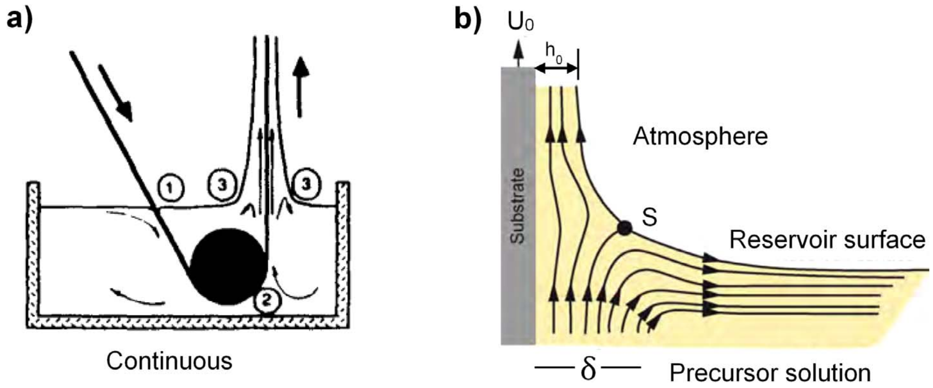

Fig. 2. (a) Stages of continuous dip coating processes [31] and (b) detail of the flow patterns (streamlines) during the dip coating process [32].

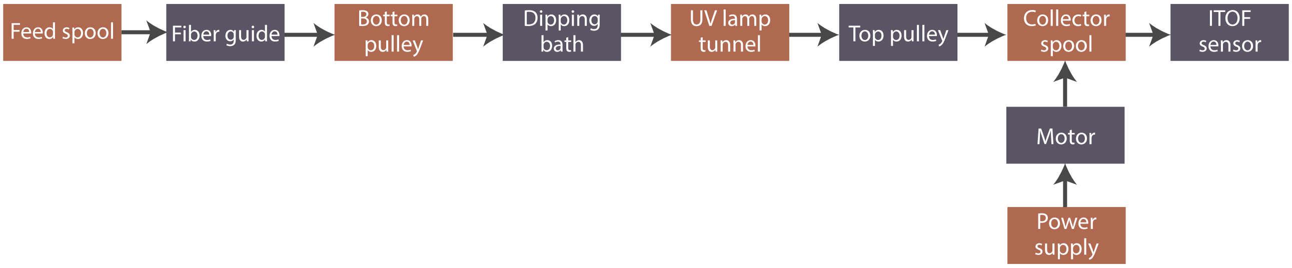

Fig. 3. Flow chart of the ITOF sensor fabrication process.

Table 1
Key features of the automated ITOF coating machine.

Components	Key features
Fiber guide	Optical fiber alignment
Bearings	Less frictional force requirement
Plum-bob	Vertical alignment of the optical fiber from the bottom pulley to the top pulley
Container	Waste reduction of the TL coating material
Larger top pulley	Distribution of the stress over the ITOF sensor
Powerful UV lights	Faster curing
Mechanical brake	Drag force control

Table 2
Required power for different coating speeds for the two various crystal percentages.

	30 wt% crystals				50 wt% crystals			
Coating speeds (mms^{-1})	1.618	2.920	4.450	6.138	1.618	3.009	4.452	5.819
Drag force in terms of power (W)	0.360	0.600	0.716	1.163	0.361	0.550	0.781	0.960