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Flexible photonics in carbon and glass fiber reinforced polymers for new multifunctionality: Exploring the advances, challenges, and opportunities

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ABSTRACT

Flexible photonics, characterized by their planar design and integrated features, have surfaced as a promising technology to unlock new possibilities for multifunctionality within fiber reinforced polymer composite materials. A comprehensive review of current progress, challenges, and opportunities associated with flexible photonic integration into carbon and glass fiber reinforced polymers is provided. A systematic examination of the literature has revealed several flexible photonic technologies that have demonstrated potential for integration in composite components to monitor performance in manufacture, service, and reuse. The review highlights the advantages and limitations of the current state-of-the-art in flexible integrated photonics for making assessments of compatibility with carbon and glass fiber reinforced polymer structures. By examining proof-of-concept demonstrations, the improved performance and novel functionalities that can be achieved for industrial applications are identified. The challenges associated with the integration process, such as durability and scalability are discussed in the context of the manufacturing processes required to create composite components. The concept of integrating flexible photonics in composite structures is relatively new, hence the paper closes by highlighting opportunities for further research and development in this field.

1. Introduction

The market for composite components made from materials such as Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) is projected to have a value of USD 59.6B billion by 2026 [1]. Adding multifunctional capability to high value composite components is very desirable. As it is possible to use such multifunctionality, incorporated at the manufacturing stage, for real time in-situ sensing of structural performance [2]. The sensing capability could be used to make a case for reducing design conservatism and, in turn, reduce the total mass of a composite structure [3]. Hence, in-situ sensing enabled by flexible photonics has the potential to underpin the adoption of more sustainable approaches by reducing scrap and extending component lifetime, ultimately resulting in reduced use of resources.

A well-establish approach for introducing sensing capability into material is the embedding of optical fiber sensors [4–10]. These can be seamlessly embedded into the composite material at the manufacturing stage so that the sensors become an integral part of the composite structure, enabling an inbuilt means for continuous and reliable monitoring. Introducing optical waveguides has several benefits over electronic systems.

(i) Optical waveguides are immune to electromagnetic interference, which means unlike some electronic sensors, they do not suffer from signal degradation or data corruption when exposed to electromagnetic fields, making them particularly suitable for use in environments with high electromagnetic activity.
(ii) Their micrometre-scale cross-section means they can be discreetly incorporated within composite structures without significantly altering the material properties or performance.
(iii) Multiplexing enables numerous sensing points along a single optical cable allowing simultaneous monitoring of various parameters at different locations within the composite material.

One of the most established techniques for incorporating optical sensing in composite material is based on the use of Fiber Bragg Gratings (FBGs) set up so that changes in Bragg wavelength can be related to the strain or temperature changes longitudinal to the fiber. These are typically referred to as quasi-distributed as the gratings have a defined

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spatial location and are interrogated through temporal, frequency, spectral or a combination thereof when multiplexed. Other common types of monitoring use scattering techniques, most commonly Rayleigh scattering offer fully distributed monitoring capability at scale [11]. In the present paper, the review seeks to explore beyond these well-established techniques that all utilise optical fiber, instead we explore flexible planar optical substrates, so called ‘flexible photonics’, conceptually illustrated in Fig. 1. These platforms can utilise the established sensing techniques in optical fiber through use of planar optical waveguides. Furthermore, through use of integrated optical circuits new sensing capability and functionality (non-sensing) can be explored.

Flexible photonics are planar optical substrates that contain optical waveguides, often referred to as Planar Lightwave Circuits (PLCs) or Photonic Integrated Circuits (PICs). Compatible with regular optical fiber, these platforms offer new optical multifunctional for composite materials when integrated, going beyond previous sensing considerations described above. These include potential for optical generation, routing, processing, detection, and modulation ultimately offering new ‘smarter’ sensing capability as well as distribution of information through a composite structure using optical circuitry.

Multifunctional composite materials offer the ability to increase the efficiency, autonomy, and lifespan of a structure by performing functions that could have only be achieved using separate materials and devices. The multifunctionality can comprise elements of sensing, actuation, tunability of material properties, self-healing, localised computation, and energy storage [12–14]. At its essence, the fundamental concept revolves around integrating sub-system functionalities directly into the material, with the goal of reducing overall weight and increasing the overall efficiency of the system, for instance, the incorporation of structural batteries contributes to the reduction in the weight of electric vehicles, thereby improving their energy efficiency.

When the area of multifunctionality is examined holistically, considering the assembly of different multifunctional subsystems, it becomes evident that there is a significant intersection with the field of robotic materials [15,16], which considers full material autonomy to deal with its environment. The purpose of the review is to introduce flexible photonics, their integration into composite materials and structures, and the multifunctionality that can be achieved. The application range is described with a view to identifying new areas for research and subsequent deployment. The objective is to connect advances with the opportunities that currently exist within two interdisciplinary fields of photonics and advanced composites. The outlook is the possibility of interfacing the multifunctionality offered by the flexible photonics with other advances in multifunctionality in an effort to build a next generation of engineered materials with embedded intelligence to create a sustainable future.

The field of flexible photonics was initially inspired by the more developed area of flexible electronics. Some of the earliest examples of flexible electronics being flexible solar cells, developed in the 1960’s for space applications. Here thinning the silicon substrate of the solar cell was implemented to a point where the substrate was flexible, motivated primarily to reduce spacecraft mass [17]. Since such early developments technologies have grown specifically driven by flexible consumer electronics. Advances have included flexible light-emitting diodes, lasers, photodetectors, Field Effect Transistors (FETs), flexible batteries, stretchable logic and memory units and transient circuits [18–20].

More recently the integration of flexible electronics into high-value composite materials and structures has been considered, that go beyond mature developments of integrating electrically conducting conduits and surface mounting, e.g. for lightning-strike protection and de-icing [21]. Examples have included embedded light indicators into composite using flexible Light Emitting Diodes (LEDs) [22] and embedding electronic sensor matrices for cure process monitoring [23]. As much of the motivation behind flexible photonics has stemmed from the advancements in flexible electronics [19,24,25], it is timely to explore new optical multifunctionality opportunities offered when flexible photonics are integrated into high value composite assets.

The area of flexible photonics has been the subject of several recent and comprehensive reviews [26–29]. The purpose of the present review is not to repeat these but focus on the integration of flexible photonics into high value composite structures. The premise of the review is to be mindful of the advantages that can be accrued by combining a planar geometric structure and integrated optical circuitry. Special attention is paid to how these two features could be used in conjunction with optical fiber to provide new capability that provides future multifunctionality in composites from the manufacturing stage and remains in the structure through its life and even into reuse and recycling.

The review starts with the current state-of-the-art for flexible photonics that includes a demonstration of integration in CFRP and GFRP materials. Next the applications for the material with the integrated flexible photonic are described. This is followed by a discussion of the future opportunities demonstrated and opportunities for optically inscribed multifunctionality.

2. Integration of flexible photonics in composite materials

The first demonstrations of flexible photonics integration into fiber reinforced composite were reported in 2016 [30]. The conference paper compared two optical materials, one based on an organic modified ceramic (Ormocer®) the other based on epoxy, both prepared as flexible polymer foils, containing an optical waveguide. The Ormocer®-based foils used Ormoclad and Ormocore, inorganic-organic hybrid polymers, with noted low optical propagation loss <0.6 dB/cm at 1550 nm wavelength. Featuring a refractive index on par with fused silica, the Ormocer® foils allowed for direct optical butt-coupling to standard glass optical fibers. The epoxy-based waveguides used Epoclad and Epocore (manufactured by Micro Resist Technology GmbH). Fig. 2 presents the cross-sectional images of the two flexible photonic polymer platforms demonstrated in GFRP. It is noteworthy that in Fig. 2(b), the Ormocer® foils exhibit a non-linear profile, which could be attributed to the lower stiffness characteristics of the material.

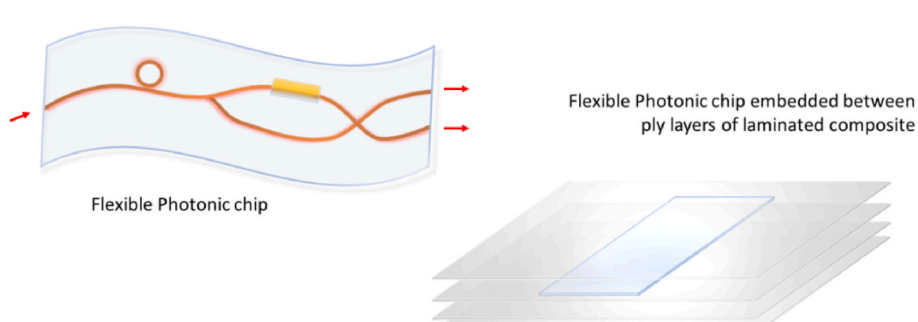

Fig. 1. Illustration depicting conceptual image of a flexible photonic chip (containing an optical circuit) and chip embedded into a laminated composite.

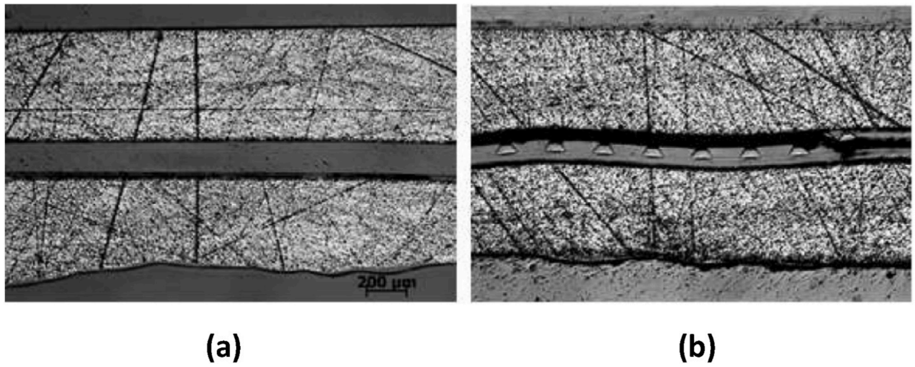

Fig. 2. First demonstration of flexible photonics in composite material, showing cross sectional images of (a) embedded epoxy (Micro Resists®) and (b) Ormocer® flexible photonics [30].

Expanding upon this initial proof-of-concept, the first occasion where strain gauge rosettes, capable of measuring strains in multiple directions within a plane, were embedded in a composite material using an integrated optic circuit on a flexible substrate [31]. Typically, such optical strain gauge rosettes are based on FBGs and consist of a single optical fiber with three lengths aligned at different angles but in the plane of the laminate, e.g. orientated at 0°, 45°, and 90° to the principal material directions. By analysing changes in the FBG wavelength the principal strains can be obtained and monitored, offering a measure of any change in performance of composite components local to the FBG rosette [32–35]. When embedding optical fiber rosettes within a composite, there are notable challenges including the potential for optical fiber crossover, which can disrupt and so compromise the mechanical integrity of the composite. Furthermore, alignment of arms on the rosette during manufacture are typically separated from each other by the order of 100 mm, introducing spatial (localisation) error in measurement. Through use of a flexible photonics circuit containing a rosette structure these challenges are obviated.

In [36] a strain gauge rosette was achieved by introducing Bragg grating corrugations using UV nanoimprint lithography and in Ref. [37] waveguides were manufactured using imprinting or laser direct-write lithography. The sensor was embedded in unidirectional glass fiber (500 g/m2 UDO E S500 from SGL Group) impregnated with a 2-component epoxy resin (RIMR135+RIMH137 from Hexion) and cured for 24 h at room temperature and a post-cured in an oven (15 h at 80 °C). The 30 μm thick sensors were noted as being fragile to handle and as seen in Fig. 3 the 50 μm sensors deformed during the embedding process because the material has a very low stiffness. This was also evident, but to a much smaller degree with sensors of thickness of 100 μm. The work reported in Refs. [36,37] did not consider any effect of the inclusion of the sensors on the structural performance of the composite or the influence of autoclave cure on the deformation of thinner films.

The second demonstration of planar optical sensors in fiber reinforced polymer composites used a fluoropolymer Cyclic Olefin Copolymers (COC) material [38]. The demonstration was carried out in prepreg woven CFRP (P3252S-25, Toray Industries, Tokyo, Japan), using the recommended autoclave cure of 7 bar at 120 °C. The planar optical sensor in this instance was rigid, with dimensions 20 mm × 10 mm x 1 mm. The large thickness of optical substrate was accommodated in the CFRP by introducing a cut-out, hence the resulting fiber discontinuity would cause a significant reduction in mechanical performance. Instead, the suitability of the sensor material COC was studied and

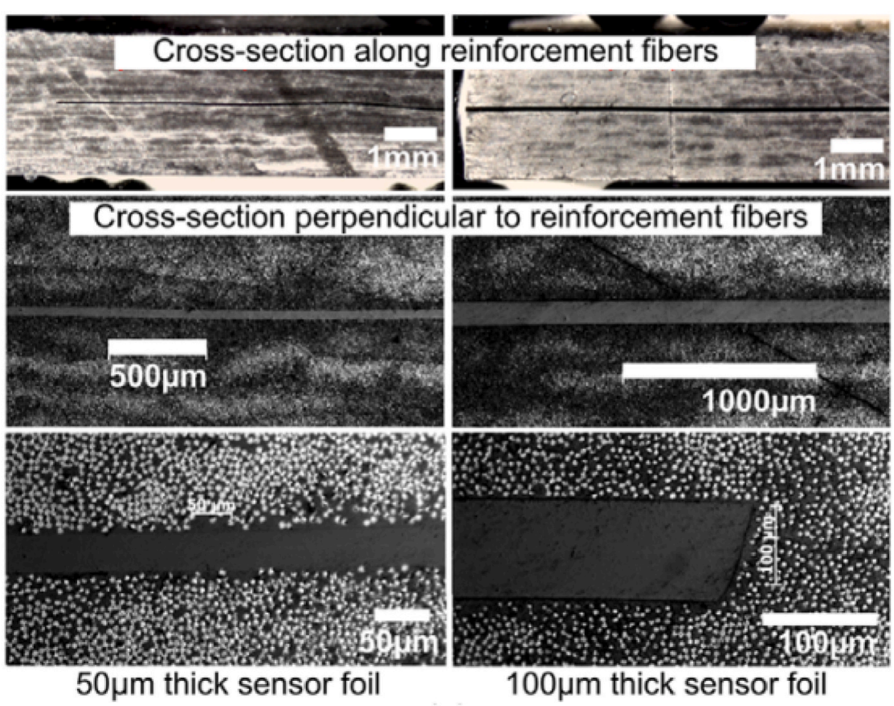

Fig. 3. Cross-sectional images (along and perpendicular to the reinforcement fibers) of 50 and 100 μm thick sensor foils embedded in a composite [31].

specifically could feasibly be thinned into a flexible substrate. Importantly, the optical waveguide survived the high temperature and pressure processing of the CFRP. Furthermore, it had a refractive index that allowed butt coupling to regular silica glass optical fiber.

Table 1 proves a list of properties of materials that have been used in integrated flexible photonic devices that are discussed in the present review. It should be noted all of these have a refractive index that enables butt coupling with silica, with low Fresnel coupling loss. It is noted that COC has a similar Young's modulus to other polymers listed in Table 1, which displayed notable deformation when integrated into composite. Therefore, it can be reasoned that COC may experience deformation of form for thicknesses of less than 100 μm. A further consideration here is that COC's thermal stability it notably lower.

Commercial composite structures can be over 100 m in length, as such there is a potential desire to integrate flexible photonics so that they can operate at these length scales. One advantage some polymer-based flexible photonics hold is scalability through roll-2-roll (R2R) manufacturing, which would address such a length scale. However, optical propagation losses need to be considered to ensure operation over such scales. Propagation losses for demonstrated platforms are listed in Table 1, these are currently high in many cases for applications at meter scale. Therefore, it is important to highlight that there has been some computational exploration aimed at achieving planarization of a silica-based polarisation-maintaining (PM) optical fiber by applying a thin polyimide coating [47]. The advantage of this approach lies in its utilization of a low optical loss substrate (doped silica), which enables long length scales. However, detailed experimental work to explore the potential propagation losses and mechanical performance on the composite is yet to take place. Moreover, addressing larger length scales comes at the cost of losing the integrated benefits and functionality associated with planar optics, such as photonic lightwave circuitry.

Flexible photonics built on doped silicate materials have incorporated the adaptation of commercial technologies originally designed for flexible displays, touchscreens, and solar panels [48,49]. These benefit from strength enhancement achieved through residual stress manipulation, e.g. ion exchange methods [50,51]. Planar photonic demonstrations using such glass families have been achieved primarily by femtosecond direct writing [52,53]. Through the optimization of laser processing parameters, it has been possible to create single-mode channel waveguides operating at 1550 nm with remarkably low propagation losses, as little as 0.11 dB/cm in all variants of flexible Willow glass formulations [51]. However, in the context of integration into composite materials, it is noteworthy that prior demonstrations for flexible photonics in silicate have not been documented. The first demonstration of flexible photonic glass into composite was achieved in doped silica, deposited through Flame Hydrolysis Deposition (FHD) [54].

FHD is a commercial process traditionally used for doped silica deposition [55,56] and the fabrication of rigid planar optics [56–60]. The process uses chloride-based precursors similar to that used in optical fiber manufacture (i.e. Outside Vapour Deposition) which ensures high purity and so low loss integrated optics to be realised [43], through photolithography or direct UV writing [61–64]. Unlike alternative glass planar deposition tools (e.g. Plasma Enhanced Chemical Vapour Deposition), FHD is consolidated at high temperatures (above 1100 °C) through use of a furnace or laser consolidation system [65,66].

Traditional PLCs, including those produced via FHD, have traditionally exhibited rigidity as a defining characteristic. Nevertheless, advances in physical machining have enabled the precise removal of a sacrificial silicon substrate, leading to the creation of a flexible glass substrate [67–71]. Through removing the silicon support in such a way, a flexible planar substrate typically 50 μm in thickness results [72]. Remarkably, flexible-FHD materials exhibit a lower Young's modulus compared to their doped-silica and silicate glass counterparts, illustrated in Fig. 4 in a plot of Young's modulus against density, i.e. a typical 'Ashby' style plot [44]. The lower Young's modulus allows the creation of sensor structures with enhanced compliance and adaptability to mechanical deformations [73]. It is noteworthy that, although the Young's modulus of flexible-FHD materials is much greater than that of polymer demonstrators, there is no discernible warping when these materials are incorporated into the composite at a thickness of 50 μm, as shown in Fig. 5. Hence, flexible-FHD material are demonstrated to have sufficient resilience to withstand the autoclave processing and are sufficiently thin to sit between the plies of a laminated composite structure. Flexible-FHD materials have the potential for seamless integration into composite material, showcasing the possibility of creating a multifunctionality in composite structures.

The resilience of FHD-silica alone has been demonstrated through survival of a 1,000,000 cycle fatigue test [44] and the inclusion of flexible FHD-silica photonics between the plies of a CFRP composite was shown to have negligible effect on the interlaminar shear strength during short beam shear (SBS) testing to EN 2563 standard) [54]. There was indeed little difference in the strength of coupons with and without the embedded FHD-silica wafer. Investigations also showed that any reduction in strength could be further mitigated by tapering the edges of the flexible photonics [54]. Edge tapering reduces geometrical discontinuity and helps to reduce the formation of epoxy-rich voids that can arise, a phenomenon well-documented and widely acknowledged in the context of embedding circular optical fibers [74]. Unlike circular optical fibers, it should be noted that the advantage of using non-circular shapes lies in the enhanced ability to exert precise geometric control over the

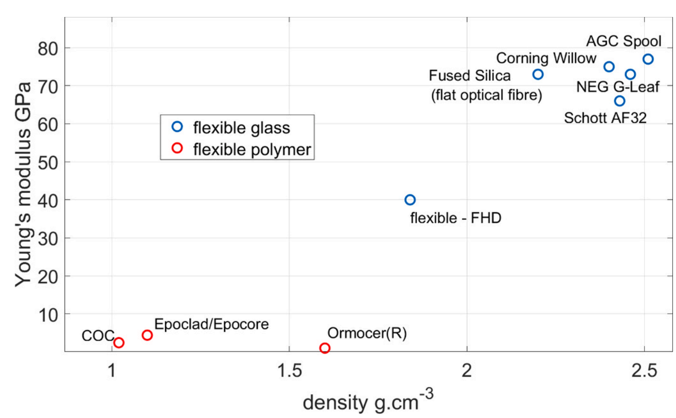

Fig. 4. An Ashby plot comparing Flexible FHD density and Young's modulus to other flexible planar glass platforms [44].

Table 1
Physical properties of flexible photonics integrated in high value composite material at standard room temperature and pressure (* specified at 1550 nm), † lowest theoretical value, based upon solid core telecommunication optical fibre.

Material	Youngs Modulus (GPa)	Thermal Stability	CTE (ppm/K)	Optical propagation loss* (dB/m)	references
Ormocer® foil (polymer)	>1	270 °C	150–180	42	[39]
Epoxy foil (Micro Resists®)	4.4	>230 °C	20–80	<60	[40]
Cyclic Olefin Copolymers	2.42	125 °C	60	125	[41,42]
FHD (doped silica)	40	>800 °C	0.55–4.3	24	[43–45]
Flat Optical Fiber	72.4	≥800 °C	0.48–0.57	0.00015†	[46]

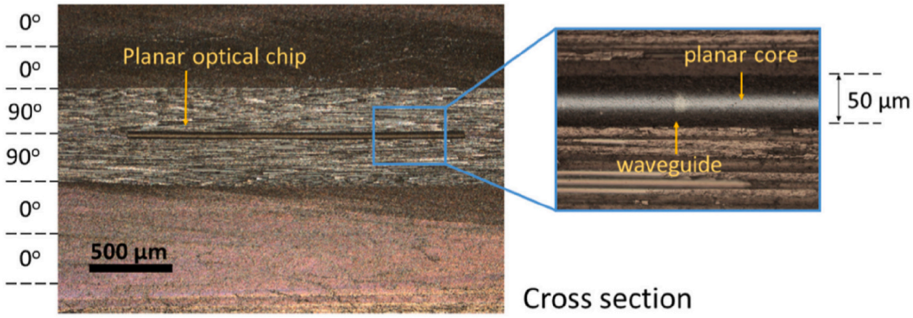

Fig. 5. cross-sectional micrograph of flexible FHD doped silica embedded into [0/0/90]s carbon fiber reinforced polymer [54].

position of the sensor between the plies to control the voids. When of sufficient stiffness the shape acts like an anchor and is subject to negligible migration in the composite during cure, which is in contrast to the documented behaviour of optical fiber.

One draw-back of FHD material is physical length scales at which it can be manufactured. Despite its advantage of lower propagation losses compared to certain polymers (as indicated in Table 1), which enables the potential for longer device length scales using the same optical powers, FHD is constrained by its dependence on a wafer-scale fabrication process. As a result, it is confined to length scales determined by the size of the sacrificial wafer, typically following the commercial standard of 8 inches. Nevertheless, there exist viable approaches for the scalability of this concept, employing techniques such as slit draw down [75] fusion draw and preform draw [76,77] techniques. These methods open potential for flexible photonics with length scales exceeding 10 m. Notably, tower drawing of flexible photonics on an optical fiber drawing tower emerges as one promising option for achieving extended length scales with minimal propagation losses, potentially reaching levels akin to those found in telecommunication-grade optical fiber (~0.1 dB/km).

The realization of flexible photonics on a drawing tower can be accomplished through three primary fabrication methods, shown schematically in Fig. 6. One method, physically machined preforms shown in Fig. 6(a), starts with a circular optical fiber preform and removes material from the top and bottom surfaces through for example ultrasonic milling or CO_2 laser machining, to achieve a planar configuration, which is then drawn [78]. The second method, vacuum assisted collapse draw shown in Fig. 6(b), has been demonstrated using a Modified Chemical Vapour Deposition (MCVD) preform, wherein a vacuum is applied to the cylindrical preform during tower drawing [79–82]. This fabrication method results in the creation of a planar glass sandwich structure, characterized by a high refractive index core positioned at its centre and enveloped by an outer cladding made of lower refractive fused silica material. Because of the mechanics involved in collapsing a cylindrical preform, the resulting structure exhibits a typical dog-bone-shaped cross-section, with a thickness so far reported typically exceeding that of commercial optical fibers, (>125 µm). This collapse draw method has leveraged various techniques, including direct laser writing [77,82] and physical machining [83] to inscribe planar circuitry. Notably, such techniques have been successfully demonstrated in applications such as sensing [76,84]. The final fabrication method, stack-and-draw approach shown in Fig. 6(c), has the unique capability to combine multiple different material elements [85]. This offers the potential for greater design flexibility that can be used to extend optical functionality. Initial demonstrations in laminated composite materials using the stack-and-draw approach, have yielded doped silica flat optical fibers with thicknesses less than those of typical optical fibers (demonstrated at <100 µm) [86]. These fibers have shown negligible mechanical degradation when subjected to SBS testing in accordance with the EN 2563 standard and the capability to be seamlessly laser-spliced to conventional optical fibers, enabling interfacing with traditional interconnects and optical components.

The next section of the paper considers optical multifunctionality for laminated composites, in the context of what and demonstrated so far opportunities that can be considered. Flexible photonics not only adds new capability, but also new opportunities for information routing and signal processing.

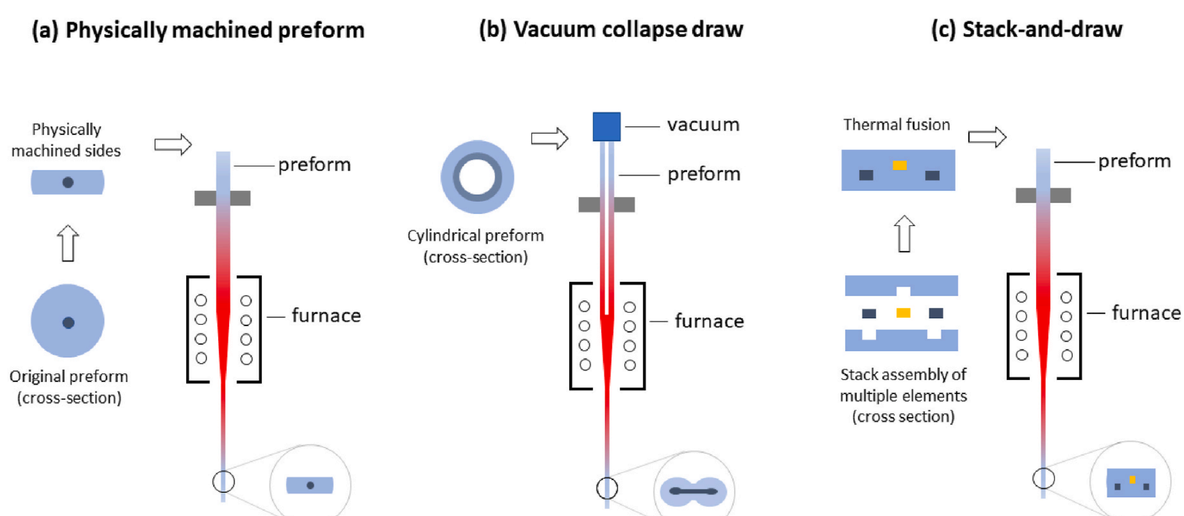

Fig. 6. Flexible photonics fabricated through use of fiber drawing tower manufacture, detailing three approaches (a) physically machined preform, (b) vacuum collapse draw, (c) stack-and-draw.

3. Creating multifunctional composites

Optical fiber integration into composites has predominantly been used for condition-based monitoring. One unique advantage of flexible photonics, which results from the planar form, is the ability to align an optical axis to the ply layer of the composite material. In particular, this is of benefit for through-thickness strain sensing. Understanding how strain distributes in the through-thickness direction of a composite material (illustrated in Fig. 7) would offer critical new insights, pivotal in detecting hidden flaws, delamination, and stress concentrations, ultimately ensuring the continued reliability and safety of composite structures. Laminated composite structures are designed to carry stress in the plane of the laminate. Strains evolving in the through-thickness direction provide an indicator of delamination and damage inception.

Existing monitoring methods primarily focus on in-plane strain measurements [8,87,88] leaving scalable through-thickness variations unexplored. Measuring through-thickness strains through use of optical birefringence changes in embedded waveguides has been considered [89–93]. In particular, the use of microstructured optical fiber is of particular interest due to its compliance and the ability to concentrate induced stresses [7,92,94–96]. Microstructured optical fiber uses the stress-optic effect [97,98] and concepts of compliant mechanics to obtain transverse strain sensitivity to over 40x compared to polarisation maintaining fiber [99]. However, there is a flaw in implementation of this concept. The cylindrical form of optical fiber means the optical axes (fast and slow) can freely twist and rotate (by angle θ) relative to the plane of the composite laminate, see Fig. 8. *A priori* determination can be made but this is rarely practical in real structures and if performed typically results in significant error, especially in cases of non-linear sensitivities [90,100].

The ability to extract through-thickness strain using 50 μm thick flexible FHD has been shown [54]. Moreover, the potential to amplify sensitivity has been explored through the incorporation of internal and external microstructured [101,102]. These findings present a compelling avenue for further research, particularly in the realms of in-process monitoring of polymer cure and in service through life assessment of composite structures.

A further advantage that flexible photonics hold for laminated composite material is the ability to utilise lightwave circuits. One very simple PLC demonstration has been a strain gauge rosette, demonstrated on 50 μm thick polymer substrates [31]. There are three key advantages over traditional optical fiber installation: (i) miniaturisation, enabling a smaller footprint of the sensor (ii) known spatial alignment of arms, as optical fiber arms can migrate during alignment/cure relative to each other (iii) seamless waveguide cross-over, that is to say waveguides can cross each other without a local increase in thickness (as happens if two optical fibers cross, which may have an influence on the structural integrity of the composite component). These advantages make flexible photonics a promising avenue for enhancing the efficiency and reliability of sensors and optical components integrated into laminated composite materials.

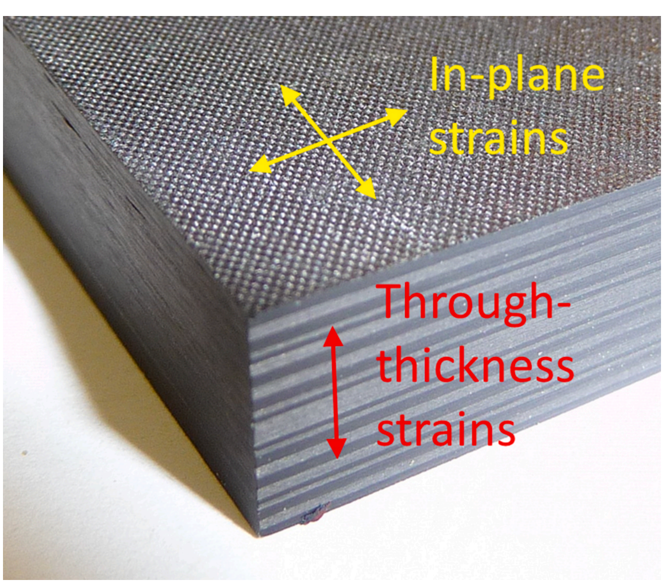

Fig. 7. linear strains in carbon fiber reinforced polymer.

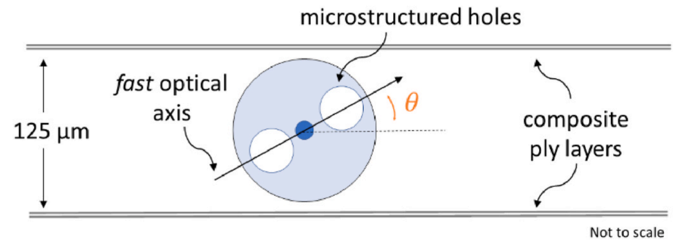

Fig. 8. Cross-sectional schematic of polarisation maintaining optical fiber (PANDA fiber) between composite ply layers. Alignment of optical axis, $\boldsymbol{\theta}$, unknown due to rotational degree of freedom.

Lightwave circuits offer a diverse range of functionalities, including light splitting and combining through Y-splitters, X-couplers, directional couplers, and Multimode Interferometers, among others. These capabilities are particularly advantageous for optimizing optical topologies and signal routing within branching architectures, as opposed to the limitations of a single optical fiber commonly found in conventional embedded concepts. This technology has the potential to significantly enhance sensor networks and signal coverage in a more efficient manner. By embedding optical splitters into composite laminates, we can draw inspiration from nature's biomimicry, mirroring the branching patterns observed in nerves or blood vessels. This efficient branching system opens the door to dynamic network rerouting, drawing insights from the telecommunications sector [103]. It is important to highlight that NxM fiber couplers can be manufactured, for instance, using techniques like fused tapering. Nevertheless, the protective casings required for these optical fiber based couplers typically have millimetre-scale thickness, which poses a potential risk to the mechanical robustness of the composite structure. Flexible photonics do not have this restriction, waveguide splitting can be achieved without increasing the total thickness of the substrate. Waveguides on the flexible platform can fan-out due to the large lateral dimension and in turn be connected to multiple optical fibers either side of the photonic circuit.

Research exploring the modulation and optical switching capabilities of simple passive components has considered a thermo-optically tuned switch, which was demonstrated in Glass Fiber-Reinforced Polymer (GFRP) composites [104]. The flexible-FHD switch was based on a Mach-Zehnder switch, with one arm phase modulated using a nichrome heater. This pioneering proof-of-concept exhibited a swift response time of 477 ± 2 μs, albeit at an electrical power consumption of 803 mW.

Another notable benefit of incorporating flexible photonics lies in its potential to introduce novel optical multifunctionality encompassing light generation, routing, processing, detection, and modulation. While substantial progress has been achieved in this field, there are several opportunities for further exploration and demonstration of these capabilities within laminated composites. This could for example include the integration of a complete optical interrogation system or communication network within the composite, requiring no optical fiber egress from the composite but instead provide a standalone, intelligent, material system.

In addition to passive components, the realm of flexible photonics extends to active devices also, as demonstrated by recent achievements in depositing robust Er^{3+} doped thin layers on flexible photonic glass substrates, specifically AS 87 eco SCHOTT glass [105]. Furthermore, future combination of flexible photonics and flexible electronics, including integrated LEDs [22] (which have successfully been demonstrated in composites) holds huge potential. It should be noted that in addition to optical sources, flexible photodetectors currently offering a 3-dB bandwidth of 1.4 GHz [106], would offer an improved spectrum of capability in composite material if combined with flexible photonics. The combination of flexible detectors, light sources, and power elements holds the potential to enable self-contained, intelligent optical monitoring systems within composite materials. Such systems may ultimately eliminate the need for optical fiber egress, enabling more autonomous optical sensing systems for composites. Thus addressing the well-documented challenges linked to the vulnerability of optical fiber egress [100,107], enabling smarter and standalone intelligent composite infrastructure [15,16].

In addition to sensing and communication, flexible photonics utilising optical phase change materials [108], offer further unique capability for integrated computation. Here a non-volatile memory that exploits the reversible phase transition between amorphous and crystalline states, stores data in a manner like traditional electronic flash memory. For high value composites, this could mean lightweight, robust, and high-density memory solutions integrated within a structure, ultimately offering potential for localised computation and greater material intelligence [109].

4. Current progress and future prospects

Recent advances have allowed the integration of flexible photonic platforms into laminated composites. However, the range of flexible photonic platforms explored thus far has been somewhat limited. This limitation can be attributed, in part, to the challenging environmental conditions encountered during the curing process, especially for high-value components necessitating autoclave curing. Such conditions involve temperatures and pressures reaching or exceeding 120 °C at 7 bar, which impose constraints on specific polymers and certain optically active materials, including those based on silicon photonics [110]. Nevertheless, the realm of flexible silicon photonics [111–113] offers exciting prospects, particularly for optical generation, processing, detection, and modulation on these platforms. Recent examples have showcased successful integration into composite-based tools, achieved through machining into the composite material itself [114]. It is worth noting that high refractive index platforms like silicon photonics pose additional challenges when it comes to packaging in conjunction with silica optical fibers, necessitating careful consideration [115]. Despite these challenges, the prospects for further advances and inclusion of future flexible photonic platforms remain promising.

It is highly desirable that flexible photonics either have low propagation loss and/or low coupling loss to silica optical fiber. The reason being that modern day composite structures and infrastructure have dimensions >1 m and so need the flexible photonics and/or fiber to scale such lengths without significant reduction in optical power. Low propagation loss flexible photonics have so far demonstrated propagation losses of the order dB/m, which could limit application at extended length scales. Here flexible photonics drawn using high purity silica doped glass have the potential to offer ultra-low loss at scale (as observed with commercial optical fiber).

A key area of interests in composites is defining more sustainable manufacturing routes that use lower temperatures and pressures than those used in autoclave consolidations. Such approaches use resin infusion and injection where lower temperatures are typically used. This could open new opportunities for other flexible photonic platforms considered, especially those based upon polymer, that may not survive tradition high temperature cures.

One flexible photonic platform type not yet explored is a hybrid system, containing, for example, both polymer and glass flexible photonics. Such platforms could provide greater sensitivity or additional functionality. For example, a through-thickness strain sensor that combines lateral stiffness of glass (so the sensor does not deform) with the compressibility of a polymer layer. Such anisotropic designs offer the potential to further tailor the sensor response preferential to detect strains in certain directions and offer an interesting and as yet unexplored capability.

5. Conclusions

The integration of flexible photonics into high-value laminated composites to create multifunctional materials holds immense promise for future development of the manufacturing and design of composite structures. The possibility to monitor performance during the product inception, manufacture, through its service life and into reuse enables a more sustainable approach in structural design. It is imperative that advantages gained through flexible photonics do not come at the degradation of the composite material or its manufacture. On this note, further exploration of the mechanical performance of composite materials and structures with integrated flexible photonics is needed. Furthermore, in the context of flexible photonics that have been mechanically tested in composite, testing has been limited to uniaxial loading cases of coupon type specimens. A deeper understanding of both the sensor performance and the effect of the sensor on the structure is required in complex geometries that experience multiaxial loading conditions to further progress this field. There is also a seamless integration question into the wide range of composite manufacture processes. The routes to integrate seamlessly at the manufacturing stage requires further investigation, particularly for more advanced procedures such as automatic tape placement. Furthermore, cross-disciplinary engagements are required to realise the revolutionary new future materials that could be enabled through flexible photonics platforms.

While significant progress has been made, the emerging field of flexible photonics presents a host of intriguing opportunities and challenges that must be addressed to unlock its full potential. One of the noteworthy aspects of this research so far is the diverse range of optical substrate materials available. Thus far however, only flexible silica-doped glass and three types of polymer material have been considered. Expanding this spectrum and exploring the unique properties of different substrates is essential to broaden the scope of flexible photonics in laminated composites.

The three critical considerations for application of flexible photonics to produce multifunctional composite structures are (i) component length scale, (ii) stiffness of the sensor platform, and (iii) effect of the sensor on the mechanical properties and performance of the component. The interplay of these three elements is vital for a successful multifunctional material. Typically, planar photonics requires only centimetre length scales, but composite structures can be significantly larger. Length scales of the flexible photonics are dictated optically by propagation loss and limitations of the manufacturing technique, where further developments may be required. From the perspective of sensing, low Young's modulus can be highly beneficial. However, if stiffness becomes too low the flexible photonics may warp when integrated into the composite (as observed with some polymer demonstrators). This is undesirable in part as if the flexible photonics is too thick (to increase stiffness) can result in the mechanical degradation of the composite.

Integration of flexible photonics into laminated composites represents an evolving frontier in materials science with much untapped potential. While challenges exist, the rewards in terms of multifunctionality and performance enhancements are substantial. As research progresses and interdisciplinary collaborations flourish, a future can be anticipated where high-value composites, augmented with flexible photonics and electronics, revolutionize various industries, unleashing innovative applications and smart materials that redefine the boundaries of materials engineering.

CRediT authorship contribution statement

Christopher Holmes: Writing – original draft, Writing – review & editing. **Janice Dulieu-Barton:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Christopher Holmes reports financial support was provided by Engineering and Physical Sciences Research Council. Christopher Holmes and Janice Dulieu-Barton have patent #US-2022-0260363-A1 pending to University of Southampton. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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