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Optical Rerouting in Glass Fibre Composite

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Abstract

We demonstrate for the first time the reconfigurability of optical signals within advanced laminated composite. The approach employs an ultra-thin planar optical circuit, embedded within glass fibre reinforced polymer (GFRP) that switches an optical input through Ohmic heating. This advance highlights new opportunities for optical reconfigurability within advanced composites, enabling data transmission redundancy and a consideration of branching optical fibre architectures.

Introduction

Embedding optical fibres into laminated composites, such as glass fibre and carbon fibre reinforced polymer is a mature technology, having had considerable developments over the past several decades^[1–3]. In these arrangements, optical fibres are typically located between the plies of the composite laminate and due to their small cross-section offer minimal intrusion, maintaining a high degree of mechanical integrity. Optical fibre offers many other advantages including an ability to multiplex many sensor elements along its length, immunity to electromagnetic interference and operate in extreme environments, such as elevated temperatures and pressures used during composite cure.

A significant challenge with embedding optical fibre within composite laminates is its susceptibility to single point failure; meaning, if the optical fibre is damaged within the

composite, there is currently no feasible route for repair. Each sensing element along an embedded optical fibre is serial sequenced point-to-point. Therefore, a shared single route of communication exists from the sensor to the external optical interrogation system, so that damage in a single location along the optical fibre results in paralysis of signals for all sensors downstream from the damage location.

Optical telecommunication networks once experienced similar limitations. In their infancy, trans-oceanic links operated in a simple point-to-point configuration. However, modern day subsea network architectures are more complex and have branching nodes to connect either full fibre pairs or portions to a trunk and/or branch fibre^[4]. This permits reconfigurability, which has transformed the reliability of our subsea communication network, offering redundancy to bypass cable damage. More broadly, optical telecommunication infrastructure adopts mesh network topologies that contains optical transport equipment capable of switching incoming to outgoing optical fibres. Our concept is to translate a similar architecture, creating reconfigurable optical fibre sensor networks within high-value complex composite structures such as those used in the aircraft.

In optical telecommunications, mesh networks are realised through optoelectronic switches, which can freely reroute signals. Conceptually, optical switches could redirect signals around damaged sections of composite structures, maintaining greater network integrity. The challenge is to achieve such capability without compromising the performance of the composite, as comprehensive monitoring capability cannot come at the expense of structural integrity. Here we build upon recently shown feasibility of embedded ultra-thin planar optics, in advanced composite material ^[5,6], developing an ultra-thin planar optical switch, that can service optical fibre in a 2x2 configuration. This is the first report of an optoelectronic switch embedded within a laminated composite. The switch utilises a planar optical circuit containing a Mach-Zehnder Interferometer (MZI) tuned electrically through a localised Ohmic heating, conceptually illustrated in **Figure 1 (a)**. This work increases optical complexity and capability

in composite material. It is envisaged that further evolution of design complexity will offer yet further multifunctionality to the composite for sensing^[5], communication^[7,8] and local computation^[9–11].

Figure 1. (a) Conceptual image of integrated optical chip (Photronics Lightwave Circuit, PLC) embedded in glass fibre reinforced polymer, the chip contains a Mach-Zehnder switch with resistive heater centred over one arm. Photograph of optical switch (b) during composite layup and (c) embedded within glass fibre polymer.

Fabrication Methodology

The MZI was fabricated using cleanroom and laser-based manufacture techniques. It is composed of a silicon wafer with 15 μm thermally grown oxide. The thick oxide layer (SiO_2) acts as an optical underclad. A core and overlaid layer are subsequently deposited, through

flame hydrolysis deposition (FHD). The core layer was designed to be UV photosensitive through doping the silicate with germanium and boron, this allowed waveguides to be written into the core layer through direct UV writing^[12]. The silicon wafer was diced to a 10 mm by 20 mm chip and hydrogenated for 1 week to further enhance photosensitivity. The MZI consisted of a pair of waveguides offset by 127 μm and two X-couplers of crossing angle 2.2°. To create a pathlength imbalance a 175 nm thick nichrome (NiCr 80/20) heating filament was deposited over one arm of the MZI through photolithography and e-beam evaporation, shown in Figure 1.

To reduce the effect of embedding the planar optical circuit on the mechanical performance of the composite, it was necessary to reduce its thickness by physically machining^[5]. Here the majority of the silicon was removed with a rastering sequence through the use of a Loadpoint MicroAce dicing saw and a synthetic diamond impregnated resin blade (DISCO R07-SD400 series). The kerf of the blade was 250 μm , a raster pitch of 90 μm , a feed rate of 5 mms^{-1} and a spindle speed of 25,000 RPM were used. The resulting surface quality had <3 μm waviness. Significant compressive residual stresses between the thermal oxide and the FHD layers resulted in warping of the chip with partial removal of the silicon^[13], and cracking of the silica layer with complete removal of the silicon. For this reason, not all the silicon was removed: the chip was embedded into the composite with a final total thickness of 300 μm .

The composite was fabricated from RP-528 unidirectional GFRP epoxy prepreg from PRF composites. GFRP was chosen due to its low electrical conductivity to minimise the risk of current leakage and short circuits; however, implementation of an insulating coating on the electrical contacts by simply encapsulating could facilitate the use within a carbon fibre based composite. The laminate (142 x 142 x 1 mm) consisted of 4 plies with a $[0/90]_s$ layup; the zero direction was parallel to the optical waveguides, illustrated in Figure 1 (a). The chip and embedded wires were placed between the central plies. The wires were lacquered single-core

copper, attached to the electrical contacts using two-part conductive silver epoxy (Chemtronics, CW2400). The composite was vacuum-bagged and debulked at room temperature for 10 minutes before curing in an autoclave under vacuum at 120°C for 1 hour at 5 bar gauge pressure. After the cure was complete the laminate was diced, with the cuts intersecting the two shorter edges of the chip to enable optical coupling. The resulting device, illustrated in **Figure 1 (b)**, contained two MZI switches separated by 1.127 mm, with two separate heating filaments. Electrical continuity was observed between the two filaments suggesting electrical bridging occurred during fabrication. Here adjacent terminals on the adjacent filaments showed a resistance of 11 Ω and 1.2 Ω respectively. The electrical resistances of the heating elements were 711 Ω and 706 Ω respectively. When wired in parallel, the resistance was 704 Ω . Two heaters were simultaneously actuated through wiring them in parallel.

Demonstration of Optical Switching

To investigate optical power splitting of the MZI one of the input waveguides was illuminated with 1306 nm laser light (Agilent, 81654A), and the output (Arm #1 and Arm #2) imaged with a near-infrared camera (Raptor Photonics, OW1.7-VS-CL-640). Power splitting was observed subject to different voltages, driven with a dual power direct current supply (Thurlby, Model 30V-1A), illustrated in **Figure 2**.

Figure 2. (a) schematic of the experimental set-up and (b) optical output of Arm #1 and Arm #2 as imaged upon near-infrared camera subject to applied voltage (c) Switching of optical power between Arm #1 and Arm #2 subject to electrical heating.

Optical power splitting, shown in **Figure 2 (c)**, was calculated by integrating the output from the captured images. It shows 2π tuning of the MZI over 1.65 W (34 V). The thermal coefficient of resistivity for nichrome is $4.1 \times 10^{-4} \text{ K}^{-1}$, meaning for an optical path length of 2 mm, a 2π phase change would correspond to a temperature change of $\sim 100 \text{ K}$, assuming a thermo-optic coefficient of $6.5 \times 10^{-6} \text{ K}^{-1}$. This relates to a 1% underestimation in power resulting from resistance variation.

From Figures 2 (b) and (c) it is noted that full power extinction for Arm #2 is not obtained, there remains $\sim 10\%$ power output. This can be explained in part due to non-symmetric splitting ratios of the X-couplers that form the MZI. Ensuring symmetric optical power splitting shall be the target for future development.

Figure 3 shows captured thermal images (FLIR, ETS320) prior (a), during (b) and immediately after (c) 1-second of Ohmic heating (potential difference set to 23 V). It shows localised heating and heat dissipation for the switch.

Figure 3. Infrared camera images showing the (a) before (b) during and (c) ~1 second after Ohmic heating. Temporal response of the embedded optical switch, showing (d) 10 Hz modulation (e) warm-up feature of heating filament and (f) cool-down.

To observe the temporal response of the switch, a 10 Hz square wave was created on a signal generator (Tektronix, AFG3021B) and amplified (New Focus, 3211) from 0 V to 23 V (0.75W). This range was chosen as the power-on segment provides an approximate π -phase change for the MZI. The optical output from Arm #1 was measured using an InGaAs amplified detector (Thorlabs, PDA 10CS-EC) with 17 MHz bandwidth, using an Olympus x20 objective. The output from the detector was triggered on a digital oscilloscope (Tektronix, TBS 1072B-EDU), shown in **Figure 3 (d)-(f)**. This shows an e^{-1} turn-off response of $477 \pm 2 \mu\text{s}$ and a turn-on response of $1.13 \pm 0.01 \text{ ms}$.

The temporal response of the buried heating filament is faster than previous observations, by a factor of two^[14]. Previous observations for similar, non-buried optical circuits had a

response of 1.02 ms for lower heat dissipation of 0.5 W. The faster turn-off response may be attributed to greater thermal conductivity, most notably on the top side of the chip.

Discussion

The first demonstration of an optoelectronic switch embedded in a laminated composite is presented. This highlights the potential for new optoelectronic functionality for composite structures, including large-scale embedded sensor networks, for structural health monitoring. Optical switching is complementary to ongoing advances in electronic multifunctionality^[15] in composites, that consist of lithographically patterned polyimide with copper. Electrical actuation could also be developed in future applications for add-drop functionality, enabling spectral multiplexed signals to be routed within composites using filtering approaches, which include those based upon Ohmic heating^[14].

The efficiency of the demonstrated switch could be further developed. Currently, for the switch to operate in one of its two states, requires a constant source of power. To improve this future designs could incorporate thermal or optically switchable materials^[16].

Conclusion

The first planar optical switch embedded into an advanced composite is presented. The optoelectronic switch highlights new optical functionality in advanced composites, as well as potential routes to overcome current limitations of single-point failure through the building blocks for fully reconfigurable optical mesh networks.

We demonstrate an integrated Mach-Zehnder switch in a glass fibre reinforced polymer composite material, driven electrically through Ohmic heating to create an optical pathlength imbalance. We obtain 2π optical switching at 1306 nm wavelength (O-band), driven by 1.65 W of electrical power with an e^{-1} switching response of $477 \pm 2 \mu\text{s}$.

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