Using Additive Manufacturing to Package and Chirp Fibre Bragg gratings

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Abstract: Additive manufacture (AM) offers a simple route to packaging components such as fibre Bragg gratings. Further, polymers with higher solid state densities than liquid state enable a simple approach to tightly fixing optical components with AM packages. With applied load and using printer directionality, chirping fibre Bragg gratings becomes possible. Information about both induced and applied stresses, and operator error, can be determined from the observed spectral shifts and chirping. Broadband gratings with bandwidths, $\Delta\lambda_{BW}>$ 7nm/cm, are demonstrated. © 2020 The Author(s)

1. Introduction

The combination of additive manufacturing (AM) and fibre Bragg gratings (FBG) potentially addresses the high cost involved with labor intensive FBG and optical fibre sensor packaging. By embedding sensor elements within 3D printed materials, a sensor can be customised for different applications with unprecedented novelty and ease. For example, 3D printed soft, flexible plastic insoles embedded with FBGs enable smart sensing for animal and human gait diagnostics [1]. 3D printing using low cost methods such as fused deposition modelling (FDM) can enable stiff, tough packages suitable for harsh environments. FDM created packages are being used to protect fibre gratings both mechanically and from water or chemical permeation across a range of infrastructure applications, from buildings to railway tracks. In most of these examples, the optical fibres are fixed, without additional effort, because polymers have a higher density solid state compared to their liquid state, leading to compression on the fibre. This greatly relaxes complexity and, with the appropriate material design possible using additive manufacturing, can negate the need for pre- or post- treatment methods. Such potential contrasts greatly with commercial work on developing FBG packaging [2,3], culminating in, for example, metal-based CNC machined packages of considerable sophistication exploiting tensile loads needed to obtain zero temperature and strain sensitivity. Here we demonstrate how these packaged can allow rapid and easy chirping of gratings for mass production of low-cost dispersion compensators and broadband filters.

2. Principles

The strong fixation of FBGs within 3D printed packages depends on design and various relaxation rates including the temperature, energy and time involved. A reference FBG sample where minimal if any tension is applied to the fibre Bragg grating is placed above an initial layer of printed ABS film. 45^0 x,y printing back and forth is used to build up the layer in the z direction, known to enable strong packages. A second overlay over the sample is then created, effectively trapping and fixing the FBG sample in place with a soft jaw-like configuration that can substantially enhance the compressive grip of the solid state. A net consequence is a slight compression on the FBG is observed for a straight but unstrained sample arising from the denser state of the polymer after solidification. Provided there is no applied strain this should be observed as a simple shift in grating peak with little change in grating profile, from which material density information can be extracted. Here, we demonstrate grating chirp by controlling the applied strain and direction of printing.

3. Experimental

All non-damage gratings ($\lambda=\lambda_B\sim 1546.3$ nm) were standard 10 mm long devices (direct writing: ArF $\lambda=$ 193 nm exciplex emission, standard conditions: pulse fluence $f_{pulse}\sim 70$ mJ/cm^2, cumulative fluence $f_{cum}\sim 85$ J/cm^2) into germanosilicate (Nufern-like GF1 [GeO$_2$] ~12 mol%) [4 and refs therein]. Measured data is collected using a commercial interrogator and extracted as images post-analysed for this work ($\Delta\lambda$ res = 0.001 nm; bandwidth variability $\Delta\lambda_{BW}\sim 0.01$ nm). These gratings are then introduced within the 3D printing process so that they are embedded within layers through compressive force upon solidification of the printing polymer.

Different applied tensions should lead to different compressive effects including chirping of the grating given the FDM printer scans from one side to the other in the zig-zag writing configuration.

Standard fused deposition modelling (FDM) based additive manufacturing is undertaken using a common thermoplastic (acrylonitrile butadiene styrene – ABS; solid density varies because of varying proportions of constituents over $\rho \sim (0.9 - 1.53)$ g/cm^3 with a median ~ (1.060 – 1.080) g.cm^{-3} [5,6]). A package was printed layer by layer. The FBG was placed on one layer before a secondary layer was printed above. The FDM passes roughly at 45^0 over the fibre axis.

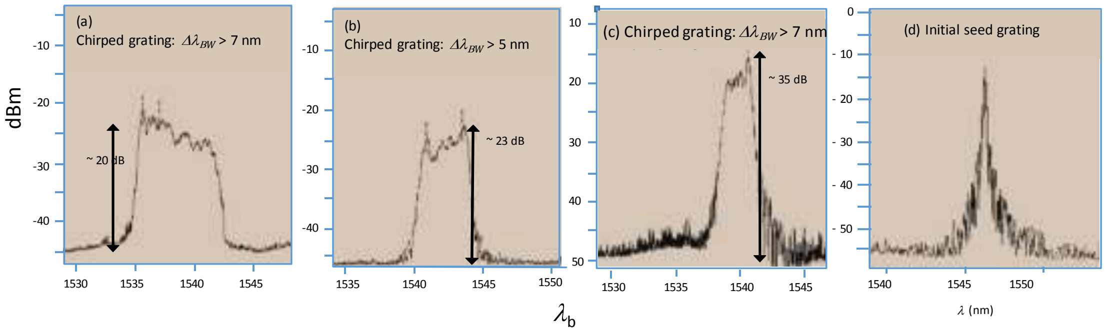

Fig. 1. Applying load stretches the FBG. Under compression packaging that load translates into a chirped spectrum as the applied tension varies during printing over one end of the FBG to the other. From (a) to (c) the spectrum bandwidth can be tuned beyond $\Delta\lambda_{BW} = 7$ nm /cm. (d) Shows the uniform grating spectra measured with no chirp and low interrogator resolution.

Given this uniformity, one can estimate from the shift to shorter wavelengths a percentage increase in density of the package of approximately 1% (or ~ 0.01 g/cm^3 from the median) when solidified. The practical ramification of this density increase is a compressive fixing of the FBG within the package, negating the need for epoxies or other materials. Another consequence is the appearance of chirp in the grating spectrum if there is an applied tension on the fibre during printing. Such chirping can also be deliberately introduced to broaden the spectral filter or to enable dispersion compensation or temporal dilation.

This occurs because the polymer quenching process as observed by the grating is dependent on two factors. One is the direction of printing – i.e. the process is NOT occurring uniformly at the same time but rather from one end to the other as the printer scans. The first print section to dry adds an additional tension when the next section starts quenching, leading to an increase or decrease in effective load, and therefore period, along the grating depending on direction. Both the mechanism and human source of error can be accommodated through automation where robots apply constant tension and 3D printing provides constant packaged deposition. Successful deployment in robotic packaging of photonic products is not new having been demonstrated by Kadence Photonics for the production of fibre thermal beam expanders, demonstrating one of the earliest industrial IoT applications in photonics and introducing the concept of industrial “fembots” [9].

In conclusion, chirped fibre Bragg gratings are fabricated easily and readily using applied tension of an optical fibre during standard 3D printing. from applied tension on the fibre that manifests itself in spectral broadening and short wavelength shift of the grating. High rates of chirp were achieved with little effort ($\Delta\lambda_{BW} \sim 7$ nm/cm). With planned tension, the potential values can be much higher still. These chirped devices can act, for example, as broadband filters, dispersion compensators or tunable variable delay lines.

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5. References

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