Technologies for high temperature fibre Bragg grating (FBG) sensors

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***Abstract*—Various types of high temperature fibre Bragg gratings (FBGs) for sensing applications, are briefly reviewed, discussing their various figures of merit and performance. References are provided to currently available commercial grade high temperature FBG sensors.**

Keywords—Fibre Bragg Gratings; High Temperature Sensing.

I. INTRODUCTION

Specialised FBGs are proving themselves in a range of industrial applications such high temperature lathe profiling [1], monitoring of fuel combustion machinery [2], regulation of diesel locomotive engine temperature [3] and to assist the structural health assessment of a building post-fire [4]. The oil, gas and geothermal industries are also set to benefit from such sensors as man's quest for fossil fuels and the lure of "free" geothermal power forces bore holes to be drilled ever deeper – a new world record only recently set with a drill depth of almost 5 km [5]. At these depths, temperatures in excess of 500 °C and extreme pressures are encountered. In this paper, an overview of ultrahigh temperature FBG sensors will be presented, updating past reviews [6,7]. In general, the higher the desired temperature of operation of *any* grating, the higher the local annealing temperature required, a general consequence arising from the relaxation continuum of an amorphous system. In these systems, the initial FBG creates a template where the glass thermal history has been periodically altered.

In the following paper, four distinct groups of FBGs will be reviewed and their various performance merits discussed. The grating types reviewed are: Type 1 and 1*n*, regenerated, femtosecond and sapphire gratings.

II. TYPE 1 & 1*N* FBGS

The simplest high temperature gratings are stabilised Type 1 FBGs. Type I FBGs are stabilised to meet telecommunication performances ($-20 \leq T \leq +80$ °C for $t > 25$yrs) but can be made to operate at much higher temperatures for shorter but still useful durations. Thermal annealing a Type 1 grating at 700 °C will reduce the FBG strength but will then operate for finite periods up to 600 °C [8]. Other approaches to stabilise Type I FBGs involve photosensitisation [9] to remove the unstable component generated during grating writing; in addition to similar thermal stability, this offers fine-tailoring of hydrogen and other species. Going to higher *T* requires regeneration.

Type 1*n* FBGs, (type IIA, negative index [10]), are gratings regenerated in various H_2-free silicate fibres [11-13]. Thermal regeneration from heating is a consequence of extended irradiation, often using UV, quasi CW or CW; similar results are feasible by using annealing alone [14]. The mechanism behind type 1*n* formation involves partial fibre relaxation of internal core/cladding stresses, in particular the radial and axial stresses induced by the UV inscription. Early Type I*n* FBGs performed to $T \sim 500$ °C before decaying [11,12]; using higher intensity exposures, generating higher local *T*, extends this to (700 - 800) °C in step-index [13] and photonic crystal fibres [15]. At lower *T*, regeneration involves the core glass. One of the advantages of type I*n* gratings is that they can be fabricated in a one-step process on existing FBG fabrication rigs, without the requirement of H_2-loading or post thermal processing.

III. ULRA-HIGH T REGENERATED FBGS

In order to extend the functionality of gratings to operate above 800 °C, silica regeneration is key [16]. Regenerated FBGs (RFBGs) of all types are fabricated by annealing a seed structure, typically but not limited to a Type 1 grating. To access the silica, and to make the process more effective, H_2 is used to further increase strain in processed regions versus those unprocessed. The hydrogen can be used during seed formation or added later during regeneration – the latter enables even draw tower gratings to be regenerated [16]. A seed Type 1 grating is regenerated (typ. $T \sim 800$ - 900 °C) in H_2-loaded germanosilicate fibre, often using a UV laser [17] but other sources are possible including fs lasers [18]. Since the changes involve silica, these gratings can survive > 1295 °C [19], 1450 °C for 20-30 mins [20]. A recent study demonstrated the continuous operation of an RFBG at 890 °C for an impressive 9000 hours [21]. Fig 1 is a reference for commercial HT-FBGs.

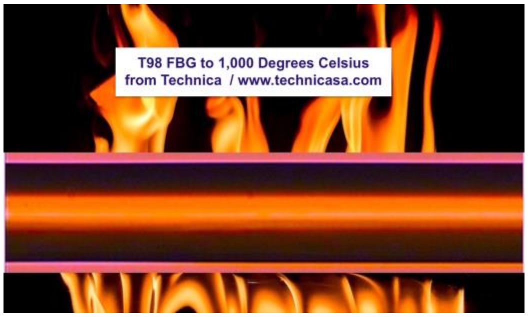


Figure 1: Commercial grade FBG to 1,000 °C.

Unlike thermal stabilization of Type 1 and Type 1n, the much higher temperatures lead to complete relaxation of fibre stresses, in core and cladding. Although now having superior stability, they will also be brittle since compressive stress between cladding and core is removed. It will happen for all fibre devices operated at similar temperatures – regeneration completes this annealing during grating fabrication rather than during application. Regenerated gratings have been used in a range of applications: high *T* glass lathe temperature profiling [1], dual P-T sensing for gas turbines [22], high *T* air flow meters for internal combustion engines [23] and train engine *T* regulation [3]. They have been used to make the first accurate measurements of fibre viscosity [24]. Complex RFBG structures such as phase-shifted gratings [25] and chirped gratings [26] have also be realized, demonstrating the high level of spatial resolution with which the regenerated structure can follow the seed. It is also possible, through the application of controlled tension loads, to even tune the final Bragg wavelength [27]. Regenerated gratings can also be readily multiplexed, with grating arrays used to monitor the distributed temperature profile of an optical fibre preform lathe [1] and a high temperature tubular furnace [28]. Figure 2 shows a commercial grade High-Temperature FBG array useable in the field for applications up to 1,000 °C.

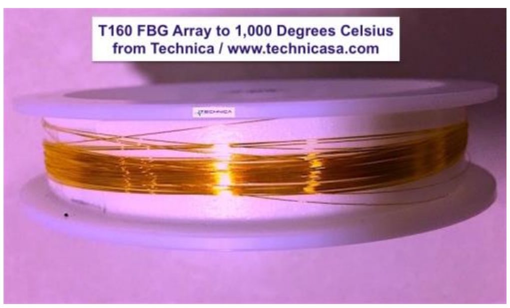
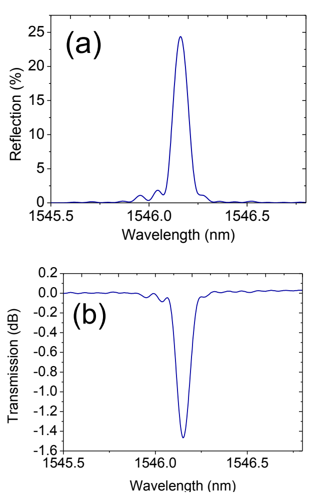


Figure 2: Commercial grade FBG Array Sensor to 1,000 °C.

Figure 3 shows typical properties of regenerated gratings inscribed in SMF-28 fibre: (a) and (b) show the clear reflection and transmission spectral profiles respectively. (c) Shows wavelength stability over several hours of operation at 1000°C.



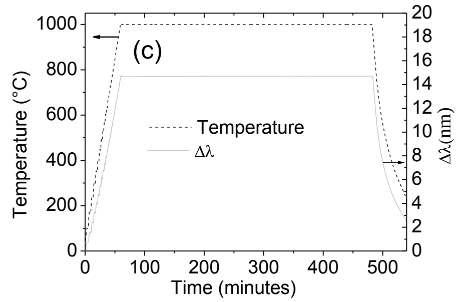


Figure 3. Typical properties of a regenerated grating fabricated in SMF-28 fibre. (a): Reflection spectrum; (b): Transmission spectrum; (c) Wavelength shift over an extended dwell time at 1000 °C. (Source: *i*PL).

IV. FEMTOSECOND FBGS

Femtosecond FBGs (fs-FBGs) are gratings inscribed using ultrafast lasers either by phase mask [29] or by point-by-point [30]. Multiphoton excitation of the silica band edge in the visible or near IR leads to finer gratings than those reported with two-photon 193 nm light [31,32]. The index change mechanism need not depend on core dopants or H_2. Femtosecond gratings fall into two categories: Type I and Type II. Type I gratings are formed by laser pulses with energy below the glass damage threshold; the index change is caused by rapid and highly localized heating and cooling of the glass, leading to localized densification and a positive index change. Type II, on the other hand, occur above the glass damage threshold where the glass is ionized leading to structural changes and a changed refractive index. Type II fs-FBGs demonstrate remarkable thermal stability up to ~ 1000 °C [34]. Furthermore, because of the very high intensity fields possible, highly localized plasma ionization and deoxygenation can lead to strong interference effects with the optical field, generating complex condensed structures such as nano gratings as well as depositing silicon (and germanium) rich regions, offering a novel route to semiconductor fabrication in glass [33]. If not scanned over a larger volume of glass, these gratings can suffer from large spectrally wide scattering losses. In terms of applications, fs-FBGs have recently been trialed as temperature sensors for monitoring fluidized bed combustors [2] and also use as radiation resistant temperatures sensors [35]. The index change is highly localized and involves significant stress-induced changes around the irradiated regions. For this reason, the higher temperature regime is limited by the thermal response of both the surrounding regions and the fibre itself which has not been relaxed prior to application. Regeneration has been shown improves fs-FBG performance [18].

V. SAPPHIRE FBGS

To go above the limits imposed by a silica system, FBGs can be inscribed in aluminium oxide or sapphire optical fibre using various approaches but particularly by femtosecond laser fabrication [36]. However, unlike conventional optical fibres that have a core and a cladding, sapphire optical fibre consists simply as a single sapphire fibre with the surrounding air as a cladding. This means there is a huge step index difference (~ 0745) and the fibre is inherently highly multimode. The large number of modes makes analysis of the reflection spectra complex and also impacts on sensitivity. The next generation of fibres that may overcome this involve hybrid mixes of silica with aluminate cores. Nevertheless, the higher melting point of these glasses means sapphire FBGs boast the highest temperature performance to date, up to 1900 °C.

Table 1 compares $d\lambda/dT$ between grating types.

TABLE 1: TYPICAL GRATING SPECIFICATIONS

Grating type	Maximum temperature (°C)	$d\lambda/dT$ (pm/°C)	Reference
Type I*n*	700	12.8 - 13.5	[9] [10]
Regenerated	1295	16.3	[15]
Femtosecond	1000	51.8	[26]
Sapphire	1900	23.0 @ room T 35.0 @ 1000 °C 35.0 @1000 °C	[28]

VI. CONCLUSIONS

A range of optical fibre Bragg gratings capable of high temperature operation have been reviewed. Gratings inscribed in conventional SMF-28 fibre can have their temperature operational limit extended depending on the fabrication technique, with regeneration yielding tolerances beyond 1295 °C. Sapphire gratings, on the other hand, extend this temperature limit much further, up to 1900 °C, addressing the limitations of conventional temperature measurement approaches such as thermocouples and pyrometers at these high temperatures. In contrast to silica waveguides they presently have major design limitations and some research is working on merging the two technologies [38].

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