Inscription methods for co-located fibre Bragg gratings using small spot direct UV writing

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Two methods to inscribe co-located fibre Bragg gratings using the small spot direct UV writing technique are described and compared, namely: superimposed gratings, which are written one over the other at the same spatial location, and superstructured gratings, where a refractive index modulation is digitally designed and all spectral signatures are written in a single step writing process. In this letter, we report a record number of 45 superimposed and 39 superstructured gratings being inscribed with an interference spot of only 14 μm in diameter.

Introduction: Fibre Bragg gratings (FBGs) are periodic refractive index structures in an optical fibre, which cause constructive interference for reflected waves of a specific design wavelength, the Bragg wavelength [1]. Oftentimes, FBGs are used for sensing applications as they are sensitive to strain and temperature; however, there are various other applications for FBGs, such as filters, grating reflectors and multiplexers [2]. Sometimes, it can be beneficial to inscribe FBGs at the same physical location; the main applications for these gratings are, for example, to increase the number of data transmission channels in wavelength-division multiplexing [3], to avoid delays in multiple frequency components in optical code-division multiplexing [4], to define grating reflectors in fibre lasers [5] or for multi-parameter sensing [6, 7].

There are two methods to fabricate FBGs on the same physical location; in this letter we will refer to them as superimposed and superstructured gratings [8]. We define superimposed gratings as being written one upon the other at the same spatial location. After the first grating is inscribed, the second grating is written on top of the first one and so on. Superstructured gratings, on the other hand, are written in a parallel writing process, where the refractive index pattern is designed and then written at once. Both techniques were first mentioned in 1978 by the same group, who had earlier that year reported the first-ever fibre Bragg gratings [9, 10]. They fabricated gratings by launching light from an argon laser into the core and creating a standing wave by reflecting light from the end facet. Superimposed gratings were fabricated by exposing the fibre with different laser sources subsequently or by launching a superimposition of different laser sources into the fibre. Since then, fabrication techniques evolved quickly; Bragg gratings are now most often inscribed by exposing the fibre transversely from the outside using UV or femtosecond light. Arigiris et al. reported the inscription of 10 superimposed gratings in a hydrogenated boron co-doped germanosilicate fibre [11], and Ibsen et al. reported the inscription of 16 superstructured Bragg gratings in deuterium loaded germanosilicate fibre [12]. These are the largest number of superimposed and superstructured gratings reported in the literature.

The small spot direct UV writing technique is a unique method of directly inscribing Bragg gratings with a very small spot size, which allows great variation in grating apodization [13]. This technique has previously been used to fabricate co-located fibre Bragg gratings in different cores of a multicore fibre [14]. In this letter, we demonstrate the fabrication of the highest number of superimposed and superstructured gratings ever reported. This is also the first time where both techniques are compared with each other.

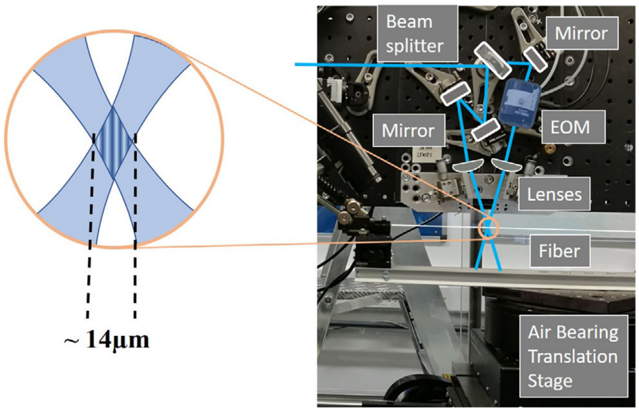

Fig 1 *Small spot direct UV writing set up: The beam of a 244 nm argon ion laser is divided into two arms and recombined in the core of a fibre, where an interference pattern is created. The fibre is translated underneath the stationary interference spot. An electro-optic modulator is placed in one arm of the interferometer, allowing the interference fringes to move along with the velocity of the fibre to imprint the Bragg grating. The Bragg wavelength can be detuned by offsetting the interference fringes from the starting position and therefore creating a different grating period in the core*

Fabrication and results: We fabricated the co-located gratings using small spot direct UV writing (SSDUW), a technique to fabricate fibre Bragg gratings by interfering two beams of a 244 nm argon ion laser and focusing and combining them to an interference spot with a diameter of 14 μm in the core of the fibre. An overview of the writing set up is shown in Figure 1. The crossing angle of $\Theta = 26.9 \pm 0.4°$ defines the pitch of the interference fringes without detuning and allows Bragg gratings to be fabricated with grating, with a period of $\Lambda = 524 \pm 8$ nm, as:

$$\Lambda = \frac{\lambda_{UV}}{2\sin\left(\frac{\Theta}{2}\right)}, \tag{1}$$

with a laser wavelength, $\lambda_{UV} = 244$ nm. An electro-optic modulator (EOM) is installed in one of the interferometer arms. Applying a sawtooth voltage to this EOM will cause the interference fringes to ‘roll and reset’. The start, reset and stop of the sawtooth wave are synchronised to the physical translation of the optical fibre such that the set of interference fringes move with the same velocity of the translation of the fibre, but can be offset from the notional position. This allows a variation of the Bragg wavelength from the grating period originally set by the crossing angle. With this technique, the inscribed period can be detuned away from the interference fringes period by ± 35 nm (resulting in a Bragg wavelength range of ± 100 nm). Further details about detuning with the small spot direct UV writing technique can be found in [15]. The slope of the sawtooth signal is defined by the velocity of the fibre’s movement. During writing, the focus of the interference spot is translated through the core of the optical fibre in the same direction as the fringe movement.

To detune from this period, and therefore to allow different Bragg wavelengths, the synchronisation can be slightly shifted. This detuning approach creates an overall slightly weaker refractive index modulation, as the period of the UV interference pattern remains unchanged. The result is a weaker grating strength for deviation of periods from the inherent period of the interference pattern, ~524 nm. Thus, the interference spot size, namely, the number of interference fringes that exist within it, defines the bandwidth over which the gratings can be detuned. As SSDUW has an interference spot diameter of 14 μm, this detuning capability is greater than that achievable with dual beam techniques using a larger interference spot.

For the work presented in this letter, a photosensitive polarisation maintaining fibre (PS-PM980) was used, as hydrogenation is a complicated process due to hydrogen depletion during writing [16]. A set of 200 mm long superimposed fibre Bragg gratings were fabricated in a pseudo-random order over a wavelength range from 1420 to 1595 nm, shown in Figure 2. This is the highest number of superimposed gratings

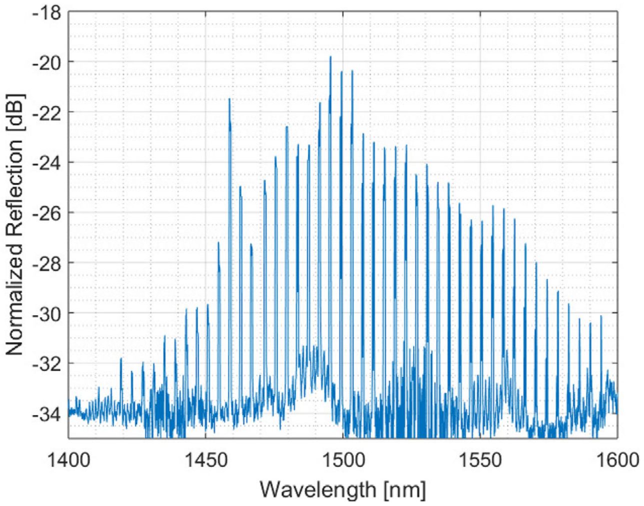

Fig 2 *Superimposed FBGs written in photosensitive, polarisation-maintaining fibre (PS-PM980) at the same physical location by inscribing one grating, returning to the start position, and writing the next grating over the previous one*

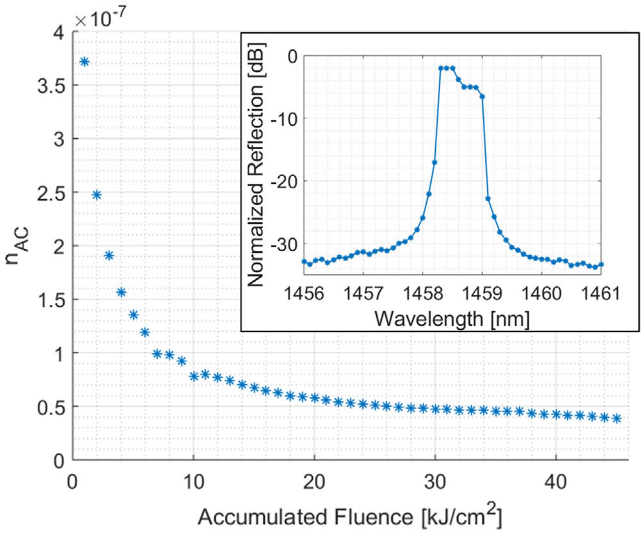

Fig 3 *Evolution of the grating contrast* n_{AC} *for the first grating at 1460 nm with further grating inscription. Each grating was inscribed with a fluence of 1 kJ/cm*^{2}*, so each accumulated fluence step is one additional grating being inscribed on top of the existing grating. The inset plot shows the spectrum of this first inscribed grating*

ever reported. The bell-shaped envelope is caused by detuning and is a characteristic for this writing technique, as different wavelengths are achieved by smearing out the interference fringes, making the individual planes slightly weaker. The grating at 1460 nm has a noticeably larger amplitude compared to the neighbouring gratings; this grating was the first grating defined in this fibre and as shown later, this comes from the photosensitivity saturation of the fibre.

Superimposed gratings are inscribed one after the other, which allows a spectrum to be taken after every inscription. With these spectra, we calculated the gratings index contrast, $n_{AC.}$, as

$$n_{AC} = \frac{\pi}{\lambda L} \operatorname{arctanh}\left(\sqrt{r_{max}}\right) \tag{2}$$

with the design wavelength λ, the grating length L and the maximum reflectivity r_{max} [1].

The evolution of the grating contrast of the first grating at 1460 nm versus accumulated fluence is shown in Figure 3. Each accumulated fluence step represents an additional grating being inscribed on top of the first grating, each with a fluence of 1 kJ/cm^2. The rapid reduction of grating strength starts to saturate after the 10th superposition and indicates that there is saturation of the photosensitivity response of the fibre.

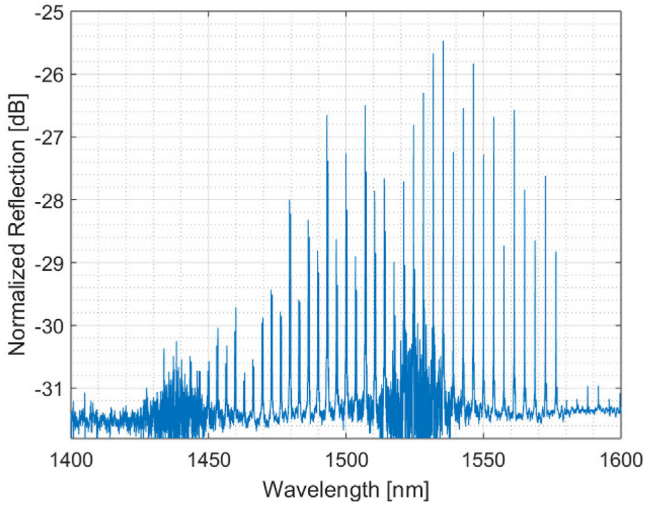

Fig 4 *The reflection spectrum of superstructured FBGs written in photosensitive, polarisation-maintaining fibre (PS-PM980) by designing a refractive index pattern and writing all gratings at once*

Superstructured gratings are written at once and therefore do not allow the grating contrast to be monitored. The n_{AC} profile of superstructured gratings are calculated with the following equation:

$$n_{AC} = \sum_{k=1}^{N/2} \sin\left(2\pi \frac{2k-1}{\Lambda_s} z + \Phi_k\right) \tag{3}$$

for k overlaid gratings, with splitting between the grating planes Λ_s, longitudinal position z and a randomised phase term Φ_k for each grating.

The optical spectrum of the superstructured gratings is shown in Figure 4. Due to the high birefringence of polarisation-maintaining fibre and the use of a broadband superluminescent source (Amonics ASLD-CWDM-5B-FA), containing 5 light sources of differing polarisation states, the gratings between 1430 and 1530 nm show two peaks, corresponding to the two orthogonal polarisation modes. This birefringence effect was observed for both superstructured and superimposed gratings. The number of reflection peaks that can be inscribed with this technique is again limited by the size and structure of the writing spot. The high spectral density of the spectral features requires a refractive index pattern with fast varying amplitude and phase, which is limited by the spot size.

To analyse the precision of both techniques, the design Bragg wavelength and the Bragg wavelength after fabrication using each technique were compared. The design Bragg wavelength over the experimental, measured real Bragg wavelength, as shown in Figure 5, with a black line of parity indicated. Deviation from a gradient of 1 indicates the error in the initial effective refractive index n_{eff} assumption used to infer the period required for a desired wavelength, whereas the offset is assumed to be related to dispersion (in addition to high order polynomial terms). This graph indicates that both writing techniques are consistently precise in grating inscription.

Figure 6 shows the boxplots comparing the two techniques regarding their precision. These boxplots show the residuals of the measured Bragg wavelength to a linear fit. This figure shows that both techniques are comparable in regard to their writing precision.

There are some differences in the practicality of both techniques during fabrication. For example, when comparing the writing time: superimposed gratings require the fibre to be translated back to the starting point. This adds approximately 6 seconds to each grating, adding just under 4.5 minutes for 45 gratings with a length of 200 mm. Superimposed gratings are primarily limited by the photosensitivity of the fibre, as indicated in Figure 3, whereas superstructured gratings have an additional potential limitation in the resolution of SSDUW's grating fringes achievable, as large numbers of close Bragg wavelengths would require fine period refractive index fringes, which require a high resolution.

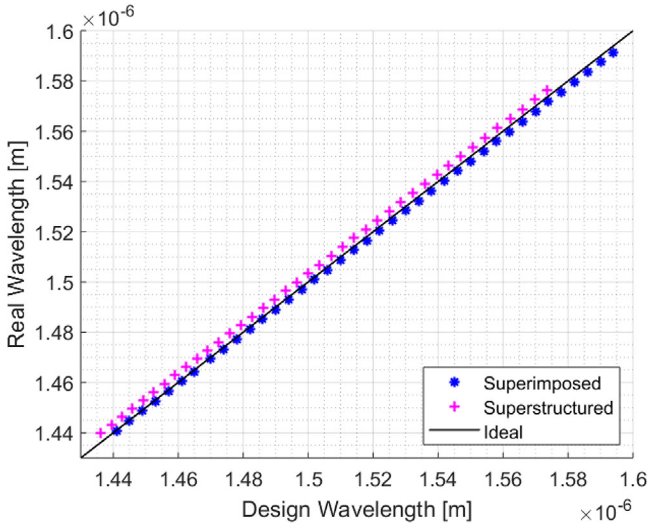

Fig 5 *Real Bragg wavelength versus design Bragg wavelength for superimposed and superstructured gratings. The black solid line indicates the ideal case, where the design Bragg wavelength is the real wavelength*

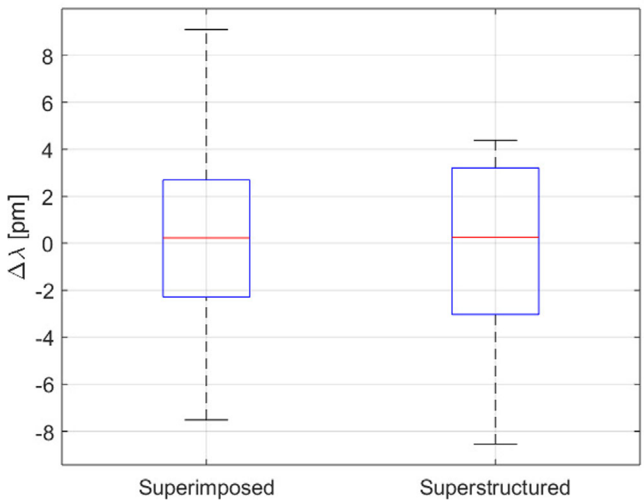

Fig 6 *Boxplots showing the precision for both the superimposed and superstructured fabrication method. This graph shows that the writing techniques are comparable in regard to their final grating precision*

Conclusion: This letter explored two different writing techniques for large numbers of co-located fibre Bragg gratings: superimposing and superstructuring. The wavelength precision for both techniques is comparable but differ in regard to their fabrication. Compared to superstructured gratings, superimposed gratings are generally more time consuming during the writing process as the fibre has to move back to the starting point. The photosensitivity of the fibre is the primary limitation for superimposed grating inscription. An additional potential limiting factor for superstructure gratings is the resolution of the refractive index structure with the interference spot.

This work shows the potential of SSDUW for fully computer controlled, precise inscription of Bragg gratings into fibre through superimposed and superstructured approaches.

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