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A simple and wavelength-flexible procedure for fabricating phase-shifted fibre Bragg gratings

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Abstract

A simple procedure for fabricating phase-shifted fibre Bragg gratings (PSFBGs) that does not require the use of a phase-shifted phase mask is presented. Two standard fibre Bragg gratings (FBGs) of equal length and with the same Bragg wavelength are inscribed sequentially in single mode optical fibre, such that the FBGs overlap physically by one grating period. This procedure induces a spectral-hole in the middle of the reflection spectrum, equivalent to a π-phase shifted FBG. PSFBGs have been fabricated in the 1300 nm and 1550 nm wavelength bandwidths, demonstrating flexibility in the choice of the centre wavelength. The PSFBGs fabricated are compared with a model based on a modified Rouard's method which is subsequently used to investigate the influence of translation stage errors on the fabrication of the PSFBGs. The model demonstrates that the strength/reflectivity of the PSFBG influences the spectral-hole linewidth as well as the finesse of the device while the length of the PSFBG affects only the linewidth of the spectral-hole but not the finesse of the device. The PSFBG devices produced by this technique are reproducible and the fabrication process is fast and is well suited for the fabrication of WDM PSFBGs.

1 Introduction

Phase-shifted fibre Bragg gratings (PSFBGs) are used widely in distributed feedback (DFB) fibre lasers, providing very stable narrow linewidth wavelength sources [1]. PSFBGs are also employed as high finesse transmission filters [2], switching elements in dense wavelength-division-multiplexing (WDM) optical communication systems [3], and as sensors [4].

A variety of techniques for the fabrication of PSFBGs have been reported previously. Limitations of these methods often include the complexity of the fabrication system, fabrication tolerance, fabrication repeatability, fabrication time, full-width-half-maximum (FWHM) of the passband of the PSFBG, cost of fabrication, and the ability to fabricate WDM PSFBGs.

A technique commonly used for producing PSFBGs uses a phase-shifted phase mask [5] in a single exposure process. The technique offers high repeatability and is fast and easy to implement. However, PSFBGs produced this way can only be written at one wavelength per phase mask. A number of phase masks will be required if WDM PSFBGs are required, making the technique relatively expensive. PSFBGs have also been fabricated using the Moiré method [6] in a double exposure process. This method fabricates two spatially co-located FBGs in a sequential exposure process. The fabrication conditions are altered between the two exposures such that the Bragg wavelengths differ slightly, e.g. by 0.3 nm. Methods that have been used to induce the difference in the Bragg wavelengths include slight tuning of the emission wavelength of the writing laser [6], spatial displacement of the fibre perpendicular to the fibre axis, i.e. either towards or away from the focusing lens [7], and the application of strain to the fibre [8] after writing the first FBG. The Moiré method requires high precision in the methods used to alter the fabrication conditions between the two exposures if the correct phase shift is to be induced. A UV post-processing technique [9] has also been investigated for PSFBG fabrication. This entails raising the local refractive index of part of an FBG by focusing a UV beam to a small spot, e.g. ~1 mm in the centre of a 4 cm long FBG [9], thereby creating a phase shift within the FBG structure. This technique requires accurate control of the beam spot-size and positioning within the FBG in order to produce the correct phase shift.

A moving fibre-scanning beam technique was used in conjunction with a uniform period phase mask [10] to fabricate PSFBGs [11] and multiple PSFBGs [12]. A high resolution stage was used to translate the fibre by an appropriate distance at the desired time while the UV beam was scanning [13]. An interferometer was implemented in order to determine accurately the position of the translation stage. A limitation of the technique is that the central wavelength of the PSFBG is limited to the wavelength of the phase mask and the technique is therefore not suited to the fabrication of WDM

PSFBGs. A commercial system, FiberGrate 2000 series (Aerotech Ltd), which offers the ability to fabricate FBGs using the point-by-point procedure with a resolution of up to 0.3 nm, has been launched [14]. The commercial system can be appropriately adopted for fabricating PSFBGs. However, the system is relatively expensive and so there is still room for the development of alternative more cost effective approaches.

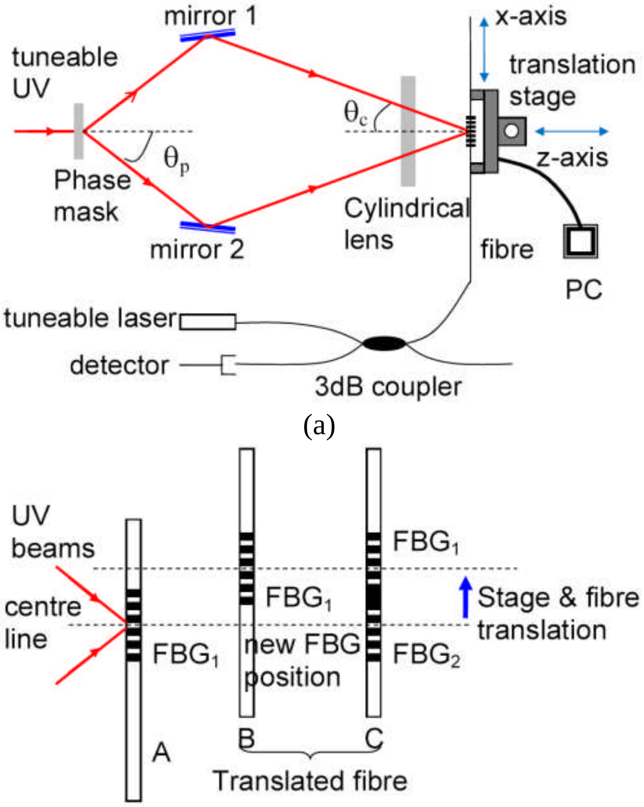
A technique that also uses a fixed, uniform period phase mask in combination with fibre translation to fabricate superstructure FBGs that incorporate single [15] and multiple [16] π-phase shifts has been demonstrated. The design of a superstructure PSFBG is however complex and also requires high precision in the translation of the fibre. A technique which utilised a continuous wave UV laser was used to fabricate FBG devices of arbitrary apodisation. The illumination intensity and phase could be changed continuously at each grating line [17]. During the writing process, the fibre was moved constantly by a high-precision air-bearing translation stage, while the UV laser beam was switched on/off using a high precision electro-optical modulator which was controlled by a customised pulse train with nanosecond timing precision. The pulse train was synchronised with the writing position. The writing procedure was repeated many times until the required reflectivity was achieved. PSFBGs were fabricated by inserting a delay in the pulse train. The technique demonstrated the capability to fabricate gratings with arbitrary apodisation and phase design but is rather complex and utilises relatively expensive components. Several other variations of the techniques discussed above have been demonstrated [18], [19] but all exhibit similar limitations. A comparison on the merits of the various techniques is provided in section 3 (Table 2).

In this paper, a procedure based upon a two-beam interferometer and fibre translation for fabricating PSFBGs is reported. The technique uses the standard FBG side writing technique [20] in a sequential double UV exposure process to fabricate PSFBGs at any required centre wavelength. Two standard FBGs of the same period are written such that they have a spatial overlap equivalent to a single grating period. The translation stage is moved once only, in order to position the fibre for the next FBG which is then written when the stage is stationary. This procedure raises the local refractive index of the central intersection of the two FBGs, leading to the formation of a phase shift. WDM PSFBGs may be fabricated over a wide spectral band, for example, fabrication in the 1300 and 1550 nm spectral bands has been demonstrated in this work.

2 Principle of the technique

The FBG fabrication system is shown in Figure 1a [20]. The phase mask is used as a beam splitter and mirrors 1 and 2 select the ± 1 diffraction orders of the UV laser beam, redirecting them to interfere at the fibre. The mirrors are mounted on rotary stages that are computer controlled to change the intersection angle θ_c, which together with the translation of the fibre along the bisector of the beams (i.e. z axis) allows FBGs of different centre wavelengths to be fabricated. A single cylindrical lens is used to focus the two beams into a line aligned with the axis of the optical fibre. The fibre is clamped onto a computer controlled translation stage (PI, M-150.11) oriented such that the direction of movement is parallel to the axis of the optical fibre. The translation stage has a maximum travel of 50 mm, a resolution of 8 nm and is backlash free.

The FBG devices were fabricated using the output from a pulsed laser operating at 248 nm, with pulse duration of 10 ns, 25 Hz repetition rate and an average power of 30 mW [20]. The FBG was interrogated using a tuneable external cavity laser source (TUNICS-Plus CL) with 1 pm resolution. The fabrication procedure involved three steps: firstly FBG_1 was written in a photosensitive singlemode (SM) fibre (Fibercore, PS1250) at a specified centre wavelength. The exposure was stopped when the required reflectivity was achieved. Secondly, the stage was translated along the x-axis under computer control through a distance equal to the length of the FBG less one grating period (Figure 1b). FBG_2 was then fabricated at the new fibre position, without changing the fabrication configuration, until the spectral-hole that developed in the middle of the FBG reflection spectrum had grown to its maximum depth and the amplitudes of the two peaks on either side of it had become approximately equal. The minimum fabrication time required for FBG_2, leading to a fully grown spectral-hole, is equivalent to the time taken to write FBG_1. The PSFBG produced by this procedure is approximately twice the length of the individual FBGs, as the spatial overlap between the FBGs is only one grating period. A rectangular aperture of width 3.00 ± 0.25 mm was positioned in the path of the UV beam from the laser to define the length of the FBGs. Diagram C in Figure 1b depicts the raised refractive index modulation in the intersection of the two FBGs, which leads to the required phase shift.



(a)

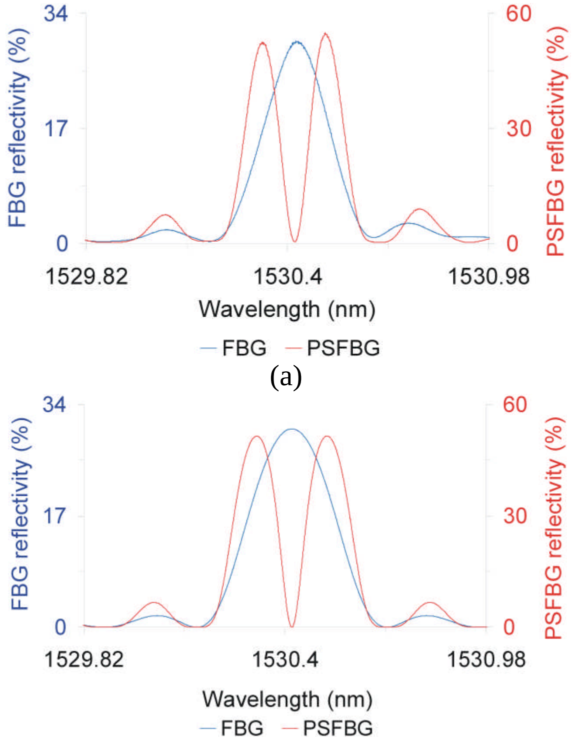
(b)

Figure 1. (a) FBG fabrication system [20] adapted to facilitate the fabrication of PSFBGs. (b) Illustrates the translation of the fibre and the locations of the 2 FBGs that compose the final PSFBG. A; FBG$_1$ location, B; position for FBG$_2$ fabrication, and C; PSFBG location showing the resulting index modulation.

3 Results and discussion

The blue curve in Figure 2a shows the reflection spectrum of a 3-mm long FBG that was written into photosensitive SM fibre (Fibercore, PS1250) at a centre wavelength of 1530.42 nm with a reflectivity of 30 %. The writing laser beam was then blocked and the stage was translated under computer control through a distance of 3 mm less one grating period (i.e. 0.528 ± 0.008 μm) along the x-axis (Figure 1b). A second FBG of the same centre wavelength was inscribed at the new fibre position using the same fabrication conditions as before. The red curve in Figure 2a shows the reflection spectrum produced by the formation of the PSFBG. The PSFBG is approximately twice the length of the individual FBGs (i.e. ~6 mm) and its reflectivity is 56 %. Figure 2b shows a reflection spectrum of the same PSFBG (52% reflectivity) which was modelled using a modified Rouard's method [21], [22]. Figure 2 shows good qualitative agreement between the experiment and the model. The lengths of the two gratings were 3.01 ± 0.01 mm and 3.00 ± 0.01 mm for FBG$_1$ and

FBG$_2$, respectively, measured with a commercial Optical Backscatter Reflectometer (OBR, Luna Technologies), which had a spatial resolution of 10 μm. These measurements are in close agreement with the value calculated from the measured grating bandwidth (3.14 mm), peak to first zero, assuming a weak grating[23], and that defined by the rectangular aperture used during grating fabrication of 3.00 ± 0.25 mm..



(a)

(b)

Figure 2. Reflection spectra of the 1st FBG written before the stage is translated (blue line) and the PSFBG (red line): (a) experimental result, and (b) theoretical result from a modified Rouard's model [22].

Figure 3 shows the reflection spectrum and the group delay for the PSFBG of Figure 2a measured by the OBR. A constant group delay is observed across the bandwidth of the PSFBG (Figure 3), as expected [23], except for a sharp peak/step occurring at the spectral-hole wavelength (1530.42 nm). This peak/step represents a group delay, $\Delta\tau$, of 0.4 ns, which corresponds to a phase shift, $\Delta\phi$, of 3.22 ± 0.07 rad, calculated from equation (1) [23].

$$\Delta\phi = \frac{2\pi c}{\lambda^2} \cdot \Delta\tau \cdot \Delta\lambda \tag{1}$$

In equation (1), $\Delta\lambda$ is the wavelength step of the OBR (0.010 nm), λ is 1530.42 nm and c is the free space speed of light.

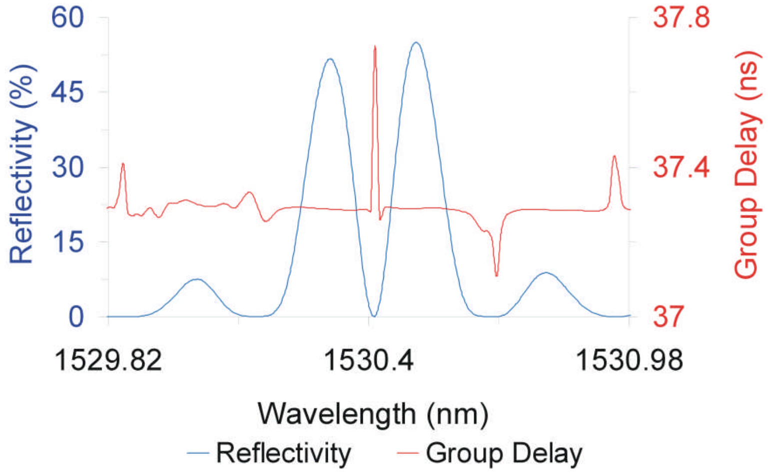


Figure 3. The reflection signal (blue line) and the group delay (red line) for the PSFBG of Figure 2a obtained by using the OBR.

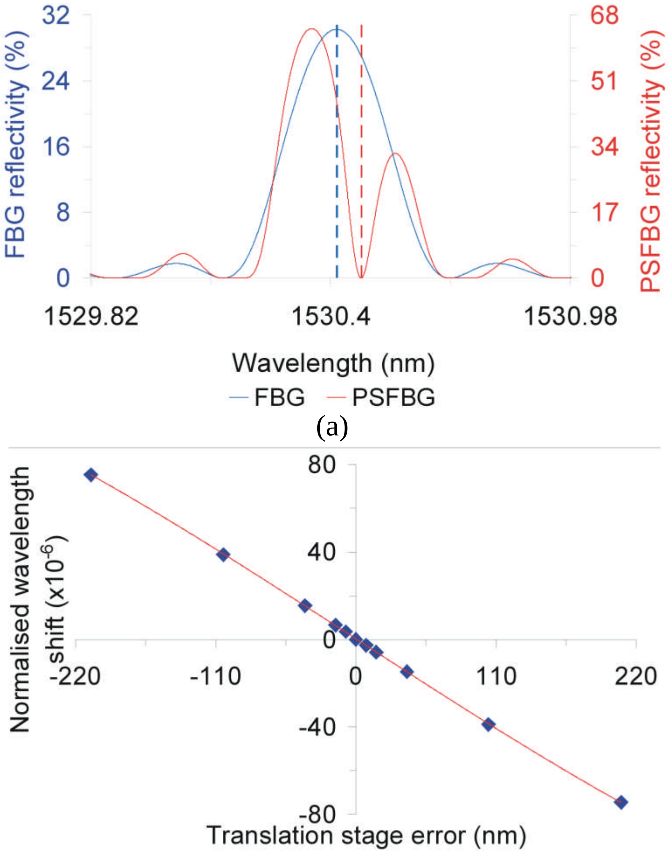
The linewidth exhibited by the spectral-hole of the PSFBG in Figure 2a was ~82 pm at full-width-half-maximum (FWHM) while the bandwidth of the transmission stop band was 0.504 nm which gives a finesse of 6.1 for this device. The finesse is comparable with that of PSFBGs fabricated using the Moiré fabrication technique [6], [8], e.g. [6] reports a finesse of ~6. The finesse can be increased significantly by fabricating PSFBGs of higher reflectivity. Table 1 shows the narrowing of the spectral-hole bandwidth of the PSFBG simultaneously with an increase in the finesse of the device if a stronger (high reflectivity) PSFBG were to be fabricated. These results were obtained using a modified Rouard’s method, demonstrating that the fabrication technique presented here is capable of producing high finesse if required. Table 1 also shows that while the bandwidth of the PSFBG spectral-hole can be narrowed by increasing the length of the device this procedure will not change the finesse.

Table 1. Quality of the PSFBGs fabricated by the new technique as a function of the length and reflectivity of the device, calculated using the modified Rouard’s method.

PSFBG Reflectivity (%)	PSFBG Length (mm)	Stop band Bandwidth (pm)	Spectral-hole FWHM (pm)	$Finesse = \frac{Stopband(bandwidth)}{SpectralHole(FWHM)}$
51	6	554	77	7.5
	12	277	38	7.3
	24	138	19	7.3
83	6	570	51	11.2
	12	284	25	11.4
	24	143	13	11.0
99	6	640	13	49.2
	12	320	6.4	50.0
	24	160	3.2	50

Linewidths of up to 11 pm and finesse of ~41 have been demonstrated for 8mm-long PSFBGs that were fabricated having high reflectivity of 97% by using phase-shifted phase masks [5]. An 8mm-long PSFBG fabricated by the new technique will have a linewidth of 16 pm and finesse of 29 if fabricated with the same reflectivity of 97 %, as analysed by the modified Rouard's method. The quality of the PSFBGs fabricated by the new technique is therefore comparable to that of PSFBGs produced by the phase-mask technique when fabricated with high reflectivity.

The influence of errors in the positioning of the fibre before the fabrication of the 2nd FBG was analysed using the modified Rouard's method. The model shows that, when the stage moves short of the intended distance, the spectral-hole of the PSFBG red-shifts in wavelength, while the opposite is true when the stage moves by more than the intended distance (Figure 4). This result shows that the fabrication method does not impose stringent accuracy to the translation of the stage, for example, an error of 8 nm in the stage position leads to a shift of 4 pm in the spectral hole wavelength while a 104 nm stage position error causes a shift of 60 pm. The line in Figure 4b represents the best fit to the modelled data points (3rd order polynomial). The transfer function can be used to determine the wavelength location of the spectral hole, prior to PSFBG fabrication, for a given translation stage error.

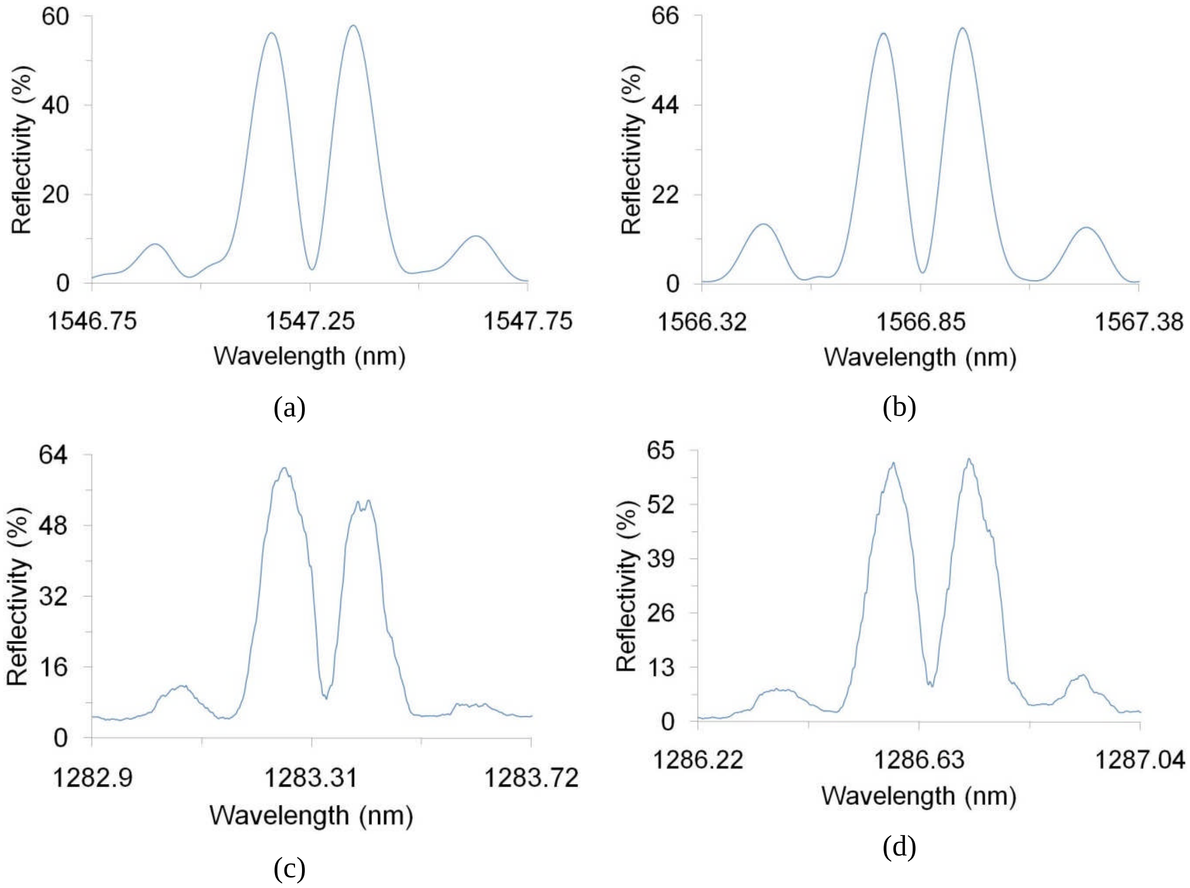


(a)

(b)

Figure 4. The influence of the stage translation error on the position of the spectral hole; (a) the spectral-hole red-shifts (dotted lines) by 60 pm when the translation stage travels 104 nm (i.e. 13 x stage resolution) short of the required distance, and (b) the shift in normalised wavelength of the spectral-hole as a function of the translation stage error. The line represents a 3rd order polynomial fit to the calculated data points.

The repeatability of the fabrication technique was investigated by writing four separate PSFBGs without altering the configuration. The spectral-hole wavelength was reproduced to within 6 pm, indicating repeatable and reproducible spectra, consistent with the theoretical model and the translation stage resolution. To demonstrate the flexibility of the technique, PSFBGs were written in the 1550 nm [24] and 1300 nm [25] wavelength bands (Figure 5). To achieve this, the angle θ_c together with the position of the translation stage along the z-axis in Figure 1, were readjusted. The spectra of the PSFBGs, shown in Figures 5a and 5b, have centre wavelengths of 1547.25 nm and 1566.85 nm, respectively, and corresponding reflectivities of 58 % and 63 %, respectively. These PSFBGs were interrogated using a tuneable external cavity laser source (TUNICS-Plus CL) with 1 pm resolution. A swept laser source (Santec Europe Ltd), with a scan range of 49 nm centred at 1287 nm and with a scan rate of 2.5 kHz, was used to interrogate the PSFBGs written in the 1300 nm wavelength band and the spectra are shown in Figures 5c and 5d. The centre wavelengths of the PSFBGs are 1283.33 nm and 1286.65 nm, respectively, measured with a resolution of 2 pm and the corresponding reflectivities are 61 % and 63 %, respectively. The spectra are slightly noisy due to the small jitter in the trigger signal of the swept laser system. Four PSFBGs fabricated by this technique, with wavelength separations of 3 nm from 1283 nm to 1292 nm, were embedded in an aircraft wing and subsequently used for aerodynamic pressure sensing [25]. This demonstrated the suitability of this fabrication system for WDM PSFBGs for sensing applications.



(a) (b)

(c) (d)

Figure 5. The reflection spectra of PSFBGs fabricated at different centre wavelengths using the configuration of Figure 1. (a) and (b) lie in the 1550 nm wavelength band, and (c) and (d) lie in the 1300 nm wavelength band.

The properties of previously reported techniques are compared with the current technique in Table 2.

Table 2. Comparison of the various PSFBG fabrication techniques

Fabrication technique	Advantages	Disadvantages	Comments
Phase-shifted phase mask [5]	- high precision - high repeatability - high quality - short writing time (typically several seconds to few minutes)	- one wavelength per mask - phase mask is relatively expensive	- can not produce WDM PSFBGs - 10 pm FWHM achieved
UV post-processing [9]	- high quality	- requires high precision - index trimming time consuming (typically up to hours) - may be difficult to implement in short FBGs	- fabrication slow - ~0.8 pm FWHM achieved - not suitable for WDM PSFBG fabrication
Moiré method [6]	- high quality - relatively short writing time - arbitrary phase shifts achieved	- requires high precision	- < 200 pm FWHM achieved - WDM PSFBGs possible when mask is not used
Moving fibre-scanning beam [11]	- long FBGs achieved - arbitrary phase shifts achieved	- PSFBGs limited to the phase mask wavelength - relatively long PSFBG device	- < 50 pm FWHM - can not produce WDM PSFBGs - 20 minutes typical writing time
Phase-shifted superstructure FBG by fibre translation but fixed uniform period phase mask [14], [16]	- High quality	- complex design and fabrication - requires high precision - relatively long PSFBG device	- can not produce WDM PSFBGs - ~0.5 - 2 pm FWHM
CW UV laser modulated by an electro-optical modulator in conjunction with sub-nanometre stage [17]	- high precision - high repeatability - versatile	- requires high precision stage - synchronisation of pulse train with writing position	- complex approach - relatively expensive components
This Paper	- short writing time (typically 5 minutes) - arbitrary phase shifts - repeatable - relaxed stage tolerance	- relatively large passband (~82 pm FWHM)	- WDM PSFBGs are achieved over a wide spectral band - fast fabrication - 82 pm FWHM

4 Conclusions

A simple procedure for fabricating phase-shifted fibre Bragg gratings (PSFBGs) has been presented. Two standard fibre Bragg gratings (FBGs) of equal length and with the same Bragg wavelength have been inscribed sequentially in single mode optical fibre, such that the FBGs overlap physically by one grating period. The characteristics of the PSFBGs fabricated compared closely with a model based on a modified Rouard’s method. The model demonstrates that the strength/reflectivity of the PSFBG influences the spectral-hole linewidth as well as the finesse of the device while the length of the PSFBG affects only the linewidth of the spectral-hole but not the finesse of the device. This model was also used to investigate the wavelength shift of the spectral hole as a function of translation stage errors which was found to be ~0.6pm/nm. PSFBGs were fabricated in the 1300 nm and 1550 nm wavelength bandwidths to demonstrate the flexibility of the technique in the choice of the grating centre wavelength. The PSFBG devices are useful for optical sensing, and have been used for example, for high resolution transverse load measurements[4], [25] .

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