two-tone optical signal will allow transmission at 1550nm over lengths of standard singlemode fibre, which are practical for deployment in mm-wave radio applications. Together with tolerance to dispersion, this approach potentially provides simple implementation and high linearity.

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Moire phase masks for automatic pure apodisation of fibre Bragg gratings

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Indexing terms: Electron beam lithography, Gratings in fibres, Masks

A Moire technique is used in the fabrication of a diffractive phase mask by electron beam lithography. The phase mask has a varying diffraction efficiency designed to produce apodised fibre Bragg gratings with a uniform ultraviolet beam exposure. Since the illumination is uniform, the average induced refractive index is constant along the grating and pure apodisation results.

Introduction: It is often required of fibre Bragg gratings (FBGs) to have high reflection in a narrow wavelength range and high transmission at all other wavelengths. Such gratings have what has been described as a high 'bandwidth utilisation factor' for increased performance in narrowband wavelength multiplexed systems [1]. To achieve such high wavelength selectivity, it is necessary to reduce the level of the reflection sidelobes which appear on both sides of the main reflection peak, because of the finite length of the grating. This sidelobe reduction, or 'apodisation', can be accomplished by varying the amplitude of the index modulation along the length of the grating [2]. Another requirement for apodisation is to linearise the dispersion compensation characteristics of chirped FBGs [3].

When apodisation is carried out by changing the ultraviolet exposure along the length of the grating, both the refractive index modulation and the average photoinduced refractive index vary. The variation of the average index leads to an undesirable effective chirp of the Bragg wavelength and widens the spectral response. Therefore, most of the methods proposed to date for the apodisation of FBGs include either a compensating, second UV irradiation with a non-modulated beam to trim the average index back to a constant value [1, 3, 4], or a system to move the fibre and/or phase mask during the exposure [5, 6]. These methods yield very good apodised responses but slow down the fabrication of fibre gratings and require better controlled and more elaborate ultraviolet exposure set-ups. An alternative approach was proposed recently in which a phase mask with a varying diffraction efficiency is used to generate both the non-uniform modulated ultraviolet fringe pattern and a compensating exposure which automatically ensures that the average photoinduced refractive index is constant [7]. The principle of operation is shown in Fig. 1.

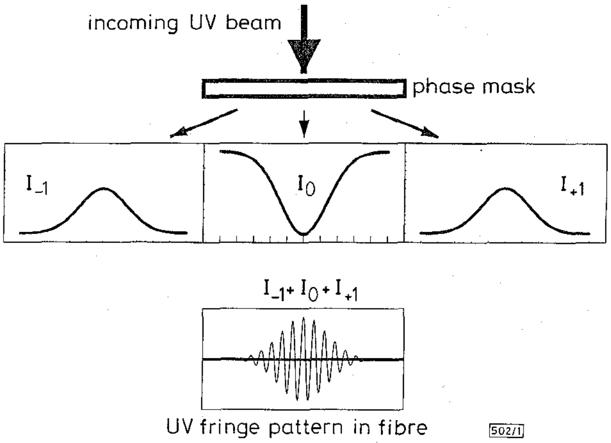

Fig. 1 *Schematic diagram of light intensity distribution behind phase mask with variable diffraction efficiency*

I_0 is spatial distribution of undiffracted light (order 0)
$I_{\pm1}$ is light diffracted in +1 and –1 orders

We assume a uniform ultraviolet exposure incident on a phase mask in which the groove shapes are varied along the length in such a way that perfect zero order nulling occurs in the centre and decreases towards the ends. This means the +1 and –1 diffracted orders will have the required bell-like intensity distribution along the grating length to generate the modulated refractive index. More importantly, since this is a transparent phase mask, the total UV exposure reaching the fibre is constant along the length and the average photoinduced index change is uniform. From a practical point of view, this approach is attractive since it does not require any modification of a standard FBG fabrication setup which uses phase mask exposure with uniform ultraviolet illumination [8]. The principle was demonstrated with a 1 mm long phase mask fabricated using a focused ion beam system and direct etching in silica [7]. The variation in groove size along the phase mask grating length was obtained by locally changing the incident ion dose. Since ion beam systems are not widely available and that longer gratings have proven difficult to fabricate, we are proposing to use the same approach but with an electron beam written phase mask (which are now commercially available).

Fabrication: A JEOL JBX-5DII high-resolution electron beam system is used to pattern the phase masks. An obvious way of changing the grating's duty cycle would be to define a pattern containing lines of varying width. On the JEOL system, the smallest increment in linewidth is 2.5nm, which allows us to increment the width from 0 to 0.5µm with no more than 200 steps. Instead, we can achieve a continuous duty cycle variation by generating a Moire fringe pattern in the electron resist with a double exposure of two 50% duty cycle gratings of slightly different periods. The phase and period of the two gratings are adjusted in such a way that the grooves overlap perfectly in the centre and are exactly out of phase by half a period at both ends. For example, in a 1cm long grating with a 1µm period, the starting points of the two electron exposures are 0.5µm apart, and one of the grating has a period shorter by 0.1nm. Therefore, over the 1cm length of the gratings, the shorter period grating has a phase shift of half a period (0.5µm) after 5mm (i.e. in the centre of the grating) and one full period after 1 cm. This is shown schematically in Fig. 2. In this example, the periods of the two gratings must differ by exactly one part in 10^4 (or 0.1 nm). To achieve such high accuracy, the grating period is adjusted by purposely mis-calibrating the gain of the beam deflection and stage motion. The upper limit of the apodised grating length achievable with this technique is fixed by the smallest mis-calibration that can be defined reliably on this electron beam system, which is roughly 1 part in 10^6. However, other factors such as stage runout [9], limit the accuracy with which the two gratings can be overlapped, so that the practical smallest mis-calibration is about 1 part in 10^5, enough to apodise a 10 cm-long, 1 μm-period grating.

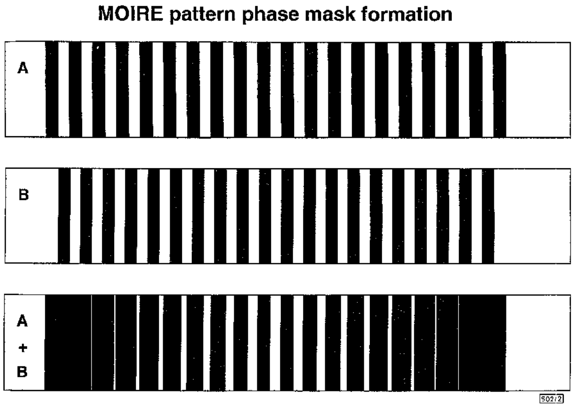

Fig. 2 *Moire groove pattern obtained in phase mask fabricated by electron beam lithography*

Electron beam writes successively on top of each other two gratings (A and B) with slightly different periods and starting points (not to scale)

Results and discussion: In the result presented here, the phase mask had a length of 8 mm and a period of 1.055 μm. Fibre Bragg gratings were photoimprinted by exposing standard hydrogen-loaded [10] telecommunication fibres trough the mask with the ultraviolet beam of a LUMONICS EX-500 ArF excimer laser operating at a wavelength of 193 nm. Gratings were photoimprinted with a single exposure ranging in time from 1 to 5 mins at 50 pulse/s and 200 mJ/cm²/pulse, without any special equipment for beam conditioning or line narrowing. The reflection spectrum of a FBG with a reflectivity of 99.99% is shown in Fig. 3, along with the theoretical spectrum of a uniform grating with the same bandwidth and maximum reflectivity. The bandwidth of an apodised grating is usually about twice that of a uniform grating of the same physical length because of the gradual decrease in index modulation at both ends. The decrease in the height of the sidelobes of the apodised grating is between 15 and 20 dB over most of the spectral range outside the main reflection peak, especially on the long wavelength side. The asymmetry in the spectral response is not fully understood at this time but is likely to be due to the poor uniformity of our ultraviolet laser beam over the 8 mm length of the grating. However, in spite of the asymmetry note that the reflectivity drops by 30 dB over < 0.2 nm on the long wavelength side of the main peak. For use in a WDM system, this 8 mm long grating has a channel width (bandwidth of transmission < –30 dB) of 0.5 nm and a minimum channel spacing (bandwidth needed for the reflection to drop below –20 dB) of 1.8 nm. This yields a bandwidth utilisation factor [1] of 28%.

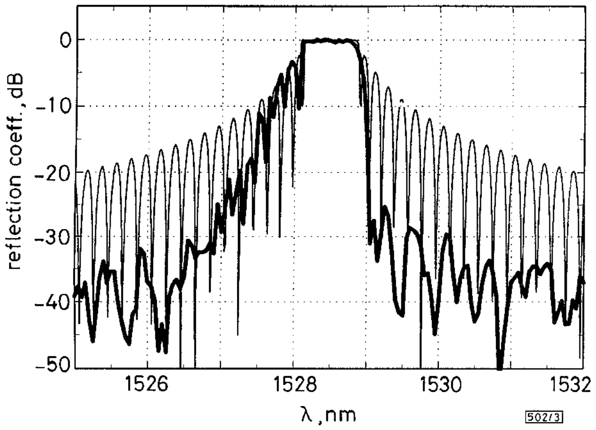

Fig. 3 *Measured reflectivity spectrum (heavy line) of 8 mm long fibre Bragg grating written with Moire phase mask*

R^{max} = 99.99%
3dB bandwidth = 0.9 nm
Thin line shows theoretical reflection spectrum of uniform grating with same reflectivity and bandwidth
—— simulation (uniform)
—— measured (apodised)

Conclusion: We have presented an efficient apodisation technique which does not require special ultraviolet exposure techniques but a more sophisticated phase mask. A simple method to fabricate the special phase mask with an electron beam lithography system was also presented. These techniques should allow fibre grating manufacturers to easily mass produce devices with improved spectral properties.

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