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Fibre Bragg grating writing using phase mask technology

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Fibre Bragg gratings (FBGs) are novel components of communication and sensors. The technique commonly employed for production of FBGs involves exposure of photosensitive germanosilicate fibre cores to intense excimer laser radiation through an optical phase mask located in close proximity of the fibre. FBGs were written using this technique in two different fibre samples and their strain and temperature sensing characteristics were investigated. The paper describes the techniques used for fabrication and their characteristic studies.

Keywords: Fibre Bragg gratings, Optical fibre devices, Optical fibre filters, Optical fibre sensors, Photosensitivity, Phase mask technique

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Introduction

Since the discovery of photosensitivity in optical fibres[1], there has been a growing interest for fabrication of Bragg gratings within the core of an optical fibre. Fibre Bragg grating (FBG) basically consists of a longitudinal periodic variation in the refractive index in the core of an optical fibre (Fig. 1). As light propagates through an FBG, Bragg diffraction causes one wavelength to be selectively reflected. The wavelength at which high reflectivity occurs is determined by the period of the grating. The research related to photosensitivity in optical fibres remained dormant for several years, mainly due to certain limitations. However, a renewed interest arose with the demonstration of the side writing technique[2]. In direct optical inscription of high quality gratings into the core of optical fibres, breakthrough has been achieved using interferometric, phase mask, and point-by-point exposure to UV laser light techniques. Gratings with a wide range of bandwidth and reflectivities can be formed on time scales ranging from a few nanoseconds to a few min, depending on the characteristics required. These gratings are low loss in-line fibre devices that can be written into the core non-invasively when and where desired, offering narrowband wavelength selection to precise specifications. As fibre gratings are highly reflective and can be directly integrated in fibre optic systems, they have enhanced or redefined nearly every aspect of optical communication systems from sources to optical amplifiers to receivers for single wavelength, wavelength-division-multiplexed (WDM), and soliton transmission. The paper highlights the basic working principle and novel features of FBGs for communication and sensor applications and describes in detail the expertise gained in fabricating FBGs using phase mask technique and their characterization.

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Novel FBG Features for Communication and Sensors

The ability to inscribe intracore Bragg gratings in germanosilicate core photosensitive fibres in the recent years has revolutionized the field of telecommunication and optical fibre based sensor technology[3,4]. Despite the improvements in optical fibre manufacturing and advancements in the field, in general, basic optical components such as mirrors, wavelength filters, and partial reflectors have been a challenge to integrate with fibre optics. Recently, however, all these have changed with the possibility to alter the core index of refraction in a singlemode optical fibre by optical absorption of UV light. This photosensitivity of fibres allows the fabrication of phase structures in their cores. These phase structures, or phase gratings, are realised by permanently changing the index of refraction in a periodic pattern along the core of the fibre. A periodic modulation of the index of refraction in the fibre core acts like a selective mirror for the wavelength that satisfies the Bragg condition given by the following equation:

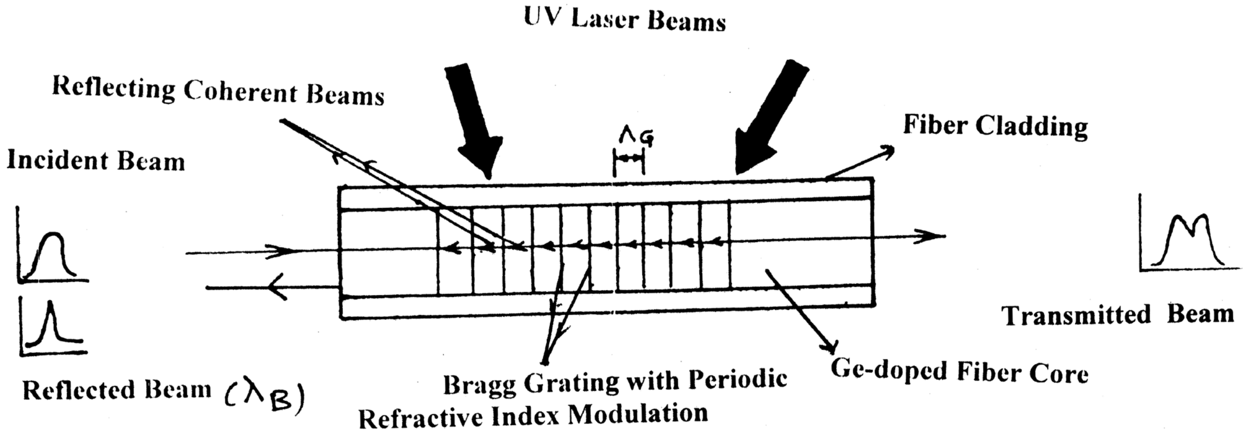

Fig. 1—Schematic diagram of an in-fibre Bragg grating

$$\lambda_B = 2n_{core}\Lambda_G, \quad \ldots (1)$$

where, λ_B is the reflected Bragg wavelength, n_{core} is the effective core index and Λ_G is the pitch of grating. This modulation of the index of refraction forms a Bragg grating. The grating period and length, together with the strength of the modulation of refractive index, determine whether the grating has a high or low reflectivity over a wide or narrow range of wavelengths[5,6]. Therefore, these parameters determine whether the Bragg grating acts as a wavelength division multiplexer in telecommunication, a narrow-band high reflectance mirror in laser or sensor applications or a wavelength selective filter removing unwanted laser frequencies in fibre amplifiers[7].

Novel and innovative Bragg grating structures owing to their unique filtering properties and versatility as in-fibre devices are finding applications in telecommunication, fibre sensors, fibre lasers and fibre amplifiers. Devices like Fabry Perot Bragg gratings for bandpass filters, chirped gratings for dispersion compensation and pulse shaping, blazed gratings for mode converters, gain equalizers for erbium doped fibre amplifiers, add/drop multiplexers and distributed and multiplexed sensors are becoming the routine lightwave applications of fibre Bragg gratings[8-10]. As FBGs are an integral part of the fibre itself, they offer a high level of mechanical convenience, simplicity, and economy to the user. These characteristics have made them very attractive for telecommunication applications. Their ability to selectively separate (by reflection) closely spaced wavelengths, e.g. makes them a useful component of add/drop and wavelength-division multiplexing devices.

Fibre optics sensing has embraced Bragg gratings since the early days of its discovery. FBGs have become almost synonymous with field itself. The nature of the output from FBGs provides fibre sensors with a built-in self-referencing capability. As the sensed information is encoded directly into wavelength, which is an absolute parameter, the output does not depend directly on the total light levels, losses in the connecting fibres and couplers, or source power. This is one of the most important advantages of FBG sensors. The wavelength encoded nature of the output, however, also facilitates wavelength division multiplexing by allowing each sensor to be assigned to a different `slice' of the available source spectrum. This enables quasi-distributed sensing of strain, temperature, or potentially other measurands by associating each spectral slice with a particular resolution[11]. Fibre sensors exploit the high sensitivity of the FBG reflected wavelengths to changes in the effective grating spacing. Mechanical strain and thermal expansion in structures, such as, airplane frames, oil tanks, and bridges can be measured precisely from changes in the reflected spectrum caused by physical deformation of the embedded fibres[12,13]. An important application of FBG sensors is in `Fibre Optic Smart Structures' where FBG sensors are embedded into structures to monitor their various parameters.

The strain and temperature sensitivity of the in-fibre grating is derived from the Bragg condition given in Eq. (1) which relates the wavelength of the reflected radiation at the line centre λ_B to the grating period Λ_G. FBG sensors can also be used to measure pressure changes and detect acoustic signals though the sensitivity is less because the glass fibre is very

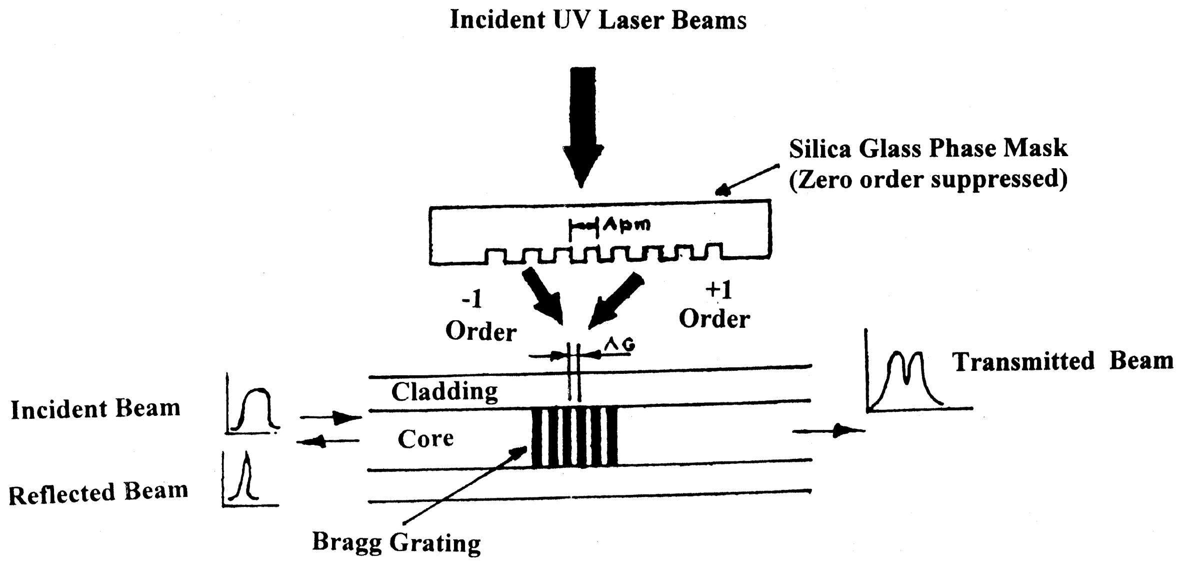

Fig. 2—Schematic representation of a typical set up for inscribing Bragg gratings in optical fibers

stiff, but some enhancement is possible by using a thick and low bulk modulus jacket They can also be used to measure electric and magnetic fields with special magnetostrictive and piezoelectric coatings on the fibre. The induced strains are small and one generally requires a read out technique, which has a fine resolution[14,15.]

Techniques for Direct Writing of FBGs

FBGs are produced by exposing a step-index germanosilicate core fibre to intense UV light, typically from a Krypton fluoride (KrF) excimer laser at 248 nm or frequency doubled argon-ion laser at 244 nm. Fig. 2 depicts the schematic representation of a typical set up for inscribing Bragg gratings in optical fibres. Absorption of this light in the germanium-doped core causes a permanent change in the refractive index of the fibre and typically, $\Delta n = 10^{-5}$ to 10^{-3}.There are three basic techniques currently in use that can produce the required high-frequency index modulation with the necessary accuracy namely, transverse holographic method, lithographic phase mask (contact print) approach, and mask projection technique[16-20].

In the holographic method, which requires a UV source with a good temporal and spatial coherence, a single laser beam is split into two components, which are subsequently recombined at the fibre to produce an interference pattern. The primary disadvantage of this technique is that the interference fringe spacing and placement is highly sensitive to the optical alignment of the system. Furthermore, maintaining adequate fringe contrast requires high mechanical stability and isolation from ambient vibration. This approach has limitations for realizing non-uniform pitch (chirped) gratings, though it has an advantage that it is flexible and allows grating parameters to be changed quickly.

The phase-mask approach utilizes a diffraction grating to split a single laser beam into several diffractive orders. Interference between the various orders creates the required pattern in the fibre. The phase-mask technique does not have the flexibility of the holographic method but is very simple to implement, far less sensitive to vibration and alignment, and requires a low coherence source, making it generally more suitable for production environments. It permits fabrication of several Bragg gratings in a single exposure thereby promising a low-cost per unit Bragg grating. This is a very attractive feature in sensor applications using 100s of sensor elements. This technique also yields high performance devices and is a very flexible process in that it can be used to fabricate gratings with different characteristics. For example, apodized Bragg gratings, chirped gratings, and core/cladding gratings formed using single pulse irradiation all have been made using a phase mask.

In the third approach based on mask-projection, a laser beam is homogenized and passed through a mask. This illuminated, striped pattern is then projected at a high reduction ratio onto the fibre.

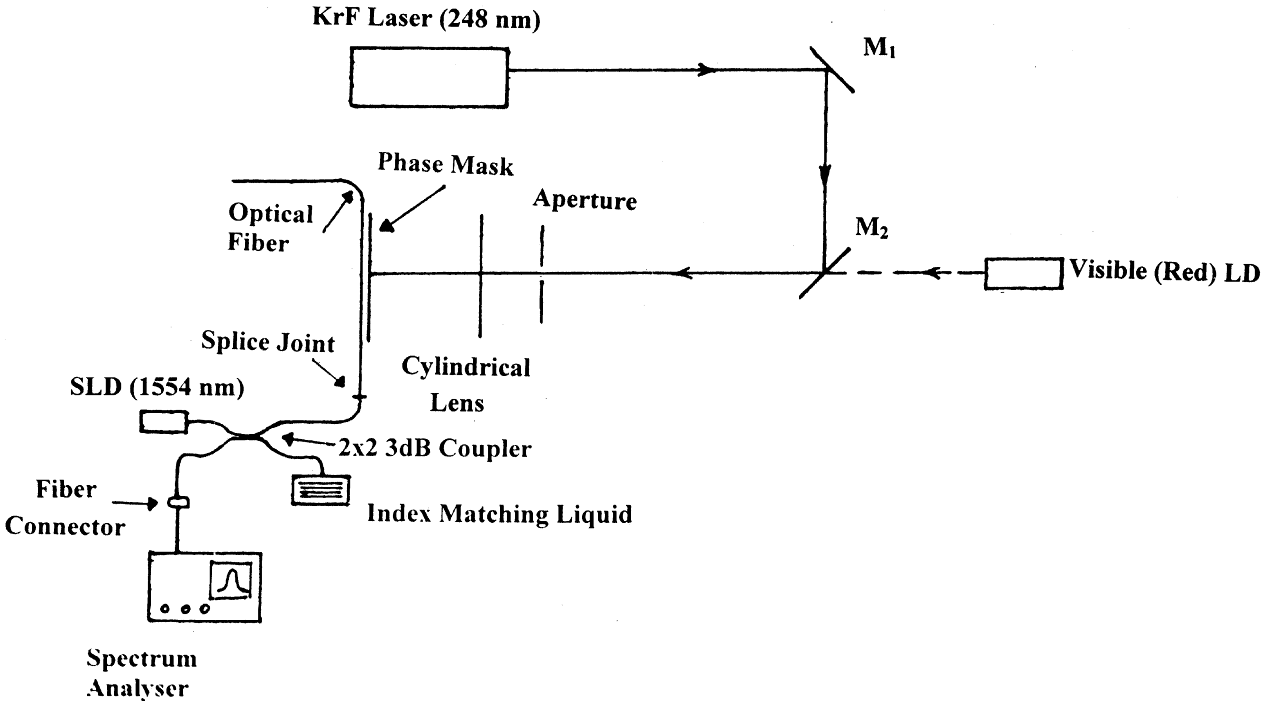

Fig. 3—Schematic of the set up used for writing FBGs

Mask projection technique can be used to produce virtually any type of complex periodic or even non-periodic structure. But, it is difficult to achieve resolutions that produce sub- micron features.

FBG Writing using Phase Mask Technology

Optical fibre gratings were fabricated# employing the optical phase mask (contact print) technique. The basic schematic of the FBGs fabrication set up used is depicted in Fig. 3. Germanosilicate core silica fibres manufactured by M/s Pirelli, Milano, Italy were used for writing gratings. The primary polymer coating of the fibre sample was removed by a stripper in a small length of about 10 mm and the fibre surface was cleaned. The UV optics is aligned using a laser diode emitting at the visible red wavelength. The bare portion of the fibre sample is placed in close proximity of a commercially available optical phase mask made in silica glass (M/s Lasiris, Canada) by means of a suitable fixture with the optical fibre axis aligned perpendicular to the grooves of the surface relief grating. The phase mask used had the grating period of 1060 nm and it has been specially designed to suppress the zero order (<5%). The UV beam from the excimer laser (Lambda Physik, Germany; Model Compex 110) passes through the phase mask at normal incidence and is diffracted in the order of ±1 beams so as to form a near-field fringe pattern. This pattern photo-imprints a modulation of refractive index onto the core of the photosensitive fibre. It follows from the geometry of the set up employed that the period of the interference fringes Λ_G is half of the one on the phase mask Λ_{pm} ($\Lambda_G = 1/2\ \Lambda_{pm}$).

The total number of excimer laser shots to be fired with typical fluence level of about 200 mJ/cm^2 /pulse) at the repetition rate of 50 Hz for writing the gratings are decided in the beginning and the computer controlled laser system is programmed accordingly. One end of the fibre sample is spliced (M/s Furukawa, Japan Splicer,Model 148S) to an output-port of a 2×2 3 dB single mode coupler. A superluminescent diode (M/s Fermionics, USA) emitting at 1554 nm is connected at the input port of the coupler and its current was set to its operating limit and the transmitted signal is monitored by means of an optical spectrum analyser (M/s Anritsu, Japan; Model MV02 Series) at the output port of the coupler for no exposure or irradiation of the sample. The laser shots are then fired and one looks for an inverted peak of wavelength, which indicates the formation of a Bragg grating. The reflectivity of the grating while in the process of being inscribed was monitored at an interval of typically 2000 shots till it reached a saturation point at which the laser is shut off. After

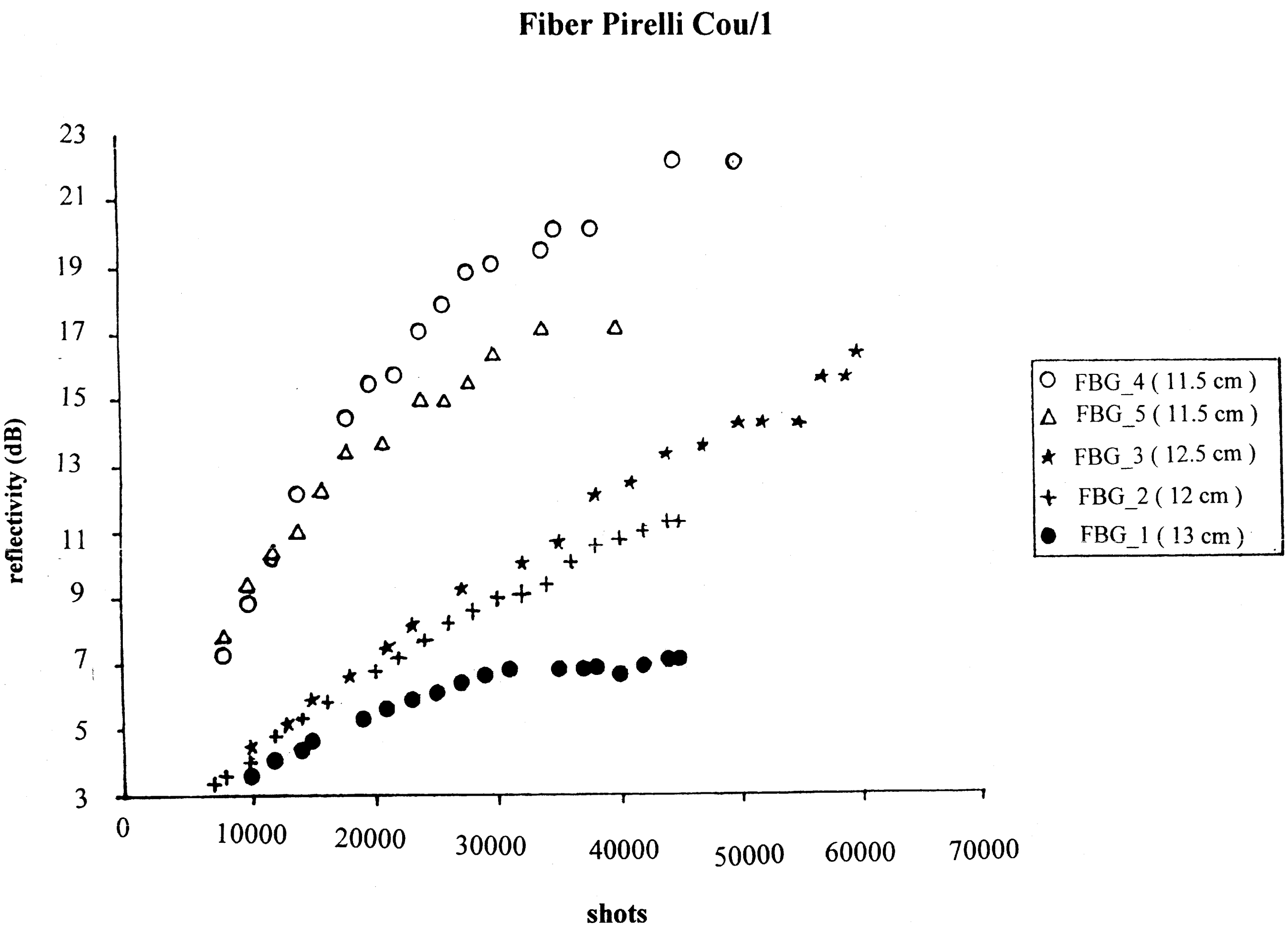

Fig. 4—Reflectivity curves of the FBGs inscribed in the fiber sample: Pirelli Cou/1

the grating has been written, its FWHM ($\Delta\lambda$) and central wavelength (λ_c) were determined by monitoring the reflected spectrum. Gratings were written on two different fibre samples (Fibre Pirelli FBG_01 and Fibre Pirelli Cou/1), using 10 mm and 15 mm apertures and choosing slightly defocused positions of the cylindrical lens so that the mask is not damaged. The inscribed grating samples were studied for their strain and temperature measurement characteristics using the optical spectrum analyser.

Results and Discussion

Figs 4 and 5 indicate the reflectivity curves for the two fibre samples: Pirelli Cou/1 and Pirelli FBG_01 respectively for various defocused positions of the lens. The gratings fabricated using the sample FBG_01 have exhibited a higher reflectivity because of higher germanium content. Fig. 6 shows the typical reflection spectrum of the inscribed Bragg gratings written in two fibre samples. The inscribed FBGs were studied for their strain and temperature measurement characteristics employing the arrangements of a piezo micropositioning stage and an oil bath respectively (Fig. 7). As evident from Figs 8 and 9, the gratings exhibit a linear variation in the shift of Bragg wavelength with strain and temperature over a wide range. Inscription of gratings was also attempted on spliced fibre joints and the corresponding reflection spectrum obtained is depicted in Fig. 10, indicating formation of a grating structure somewhat similar to a phase/index-shifted gratings. Such gratings are characterised by a very narrow transmission window in the middle of their stop band and are of potential interest for narrow band wavelength selection, multichannel wavelength demultiplexing and sub nanostrain strain measurements[21-24].

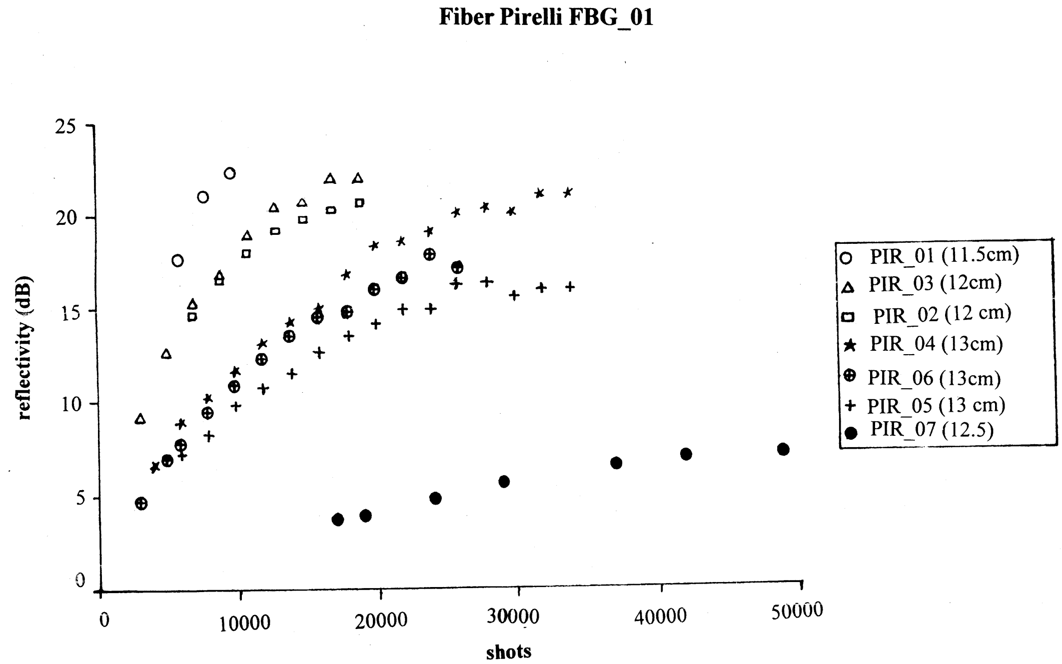

Fig. 5—Reflectivity curves of the FBGs inscribed in the fiber sample: Pirelli FBG_01

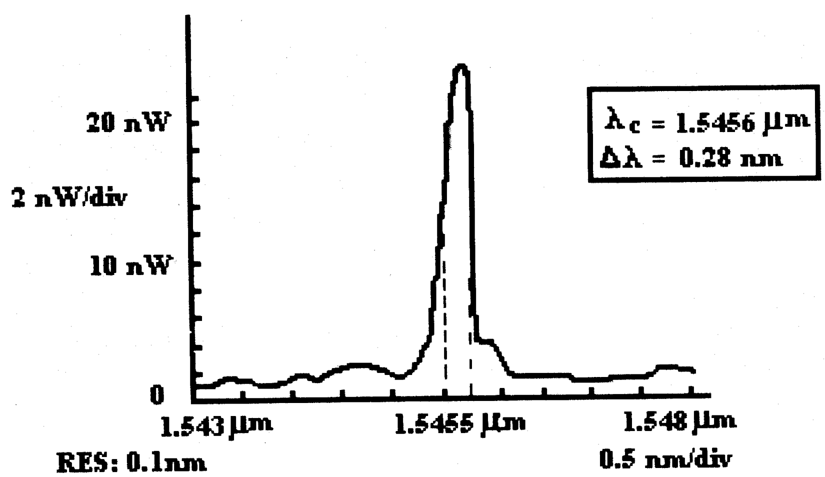

Fig. 6—Typical reflection spectrum of an inscribed FBG

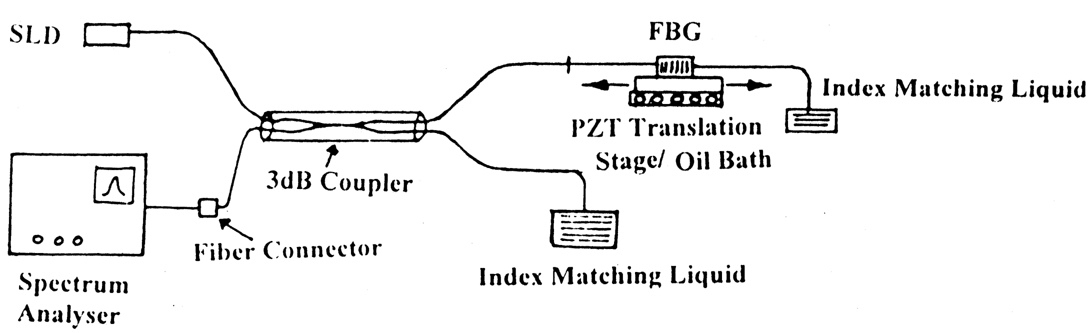

Fig. 7—Schematic of the experimental set up used for characterisation of FBGs.

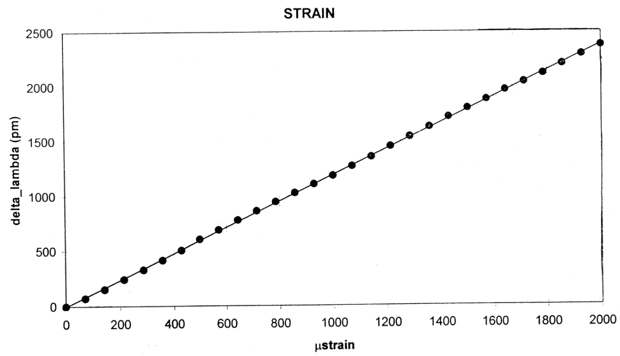

Fig. 8—Shift of Bragg wavelength with strain

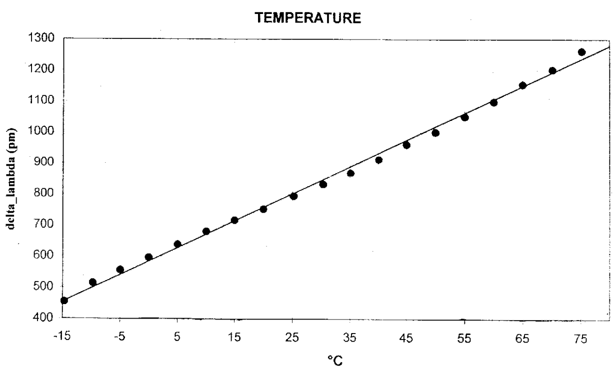

Fig. 9—Shift of Bragg wavelength with temperature

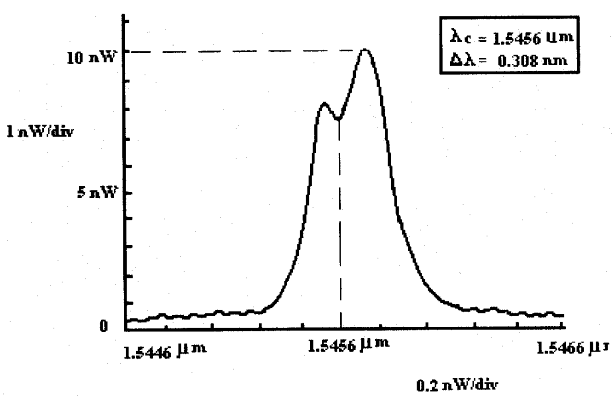

Fig. 10—Reflection spectrum of a FBG inscribed on both sides of a fiber splice

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