Information highways, fibre lasers and amplifiers, and a whole range of optical-based sensors have all been waiting for a simple grating that can be written directly into the fibre

Fibre gratings

PHILIP ST J RUSSELL, JEAN-LUC ARCHAMBAULT AND LAURENCE REEKIE

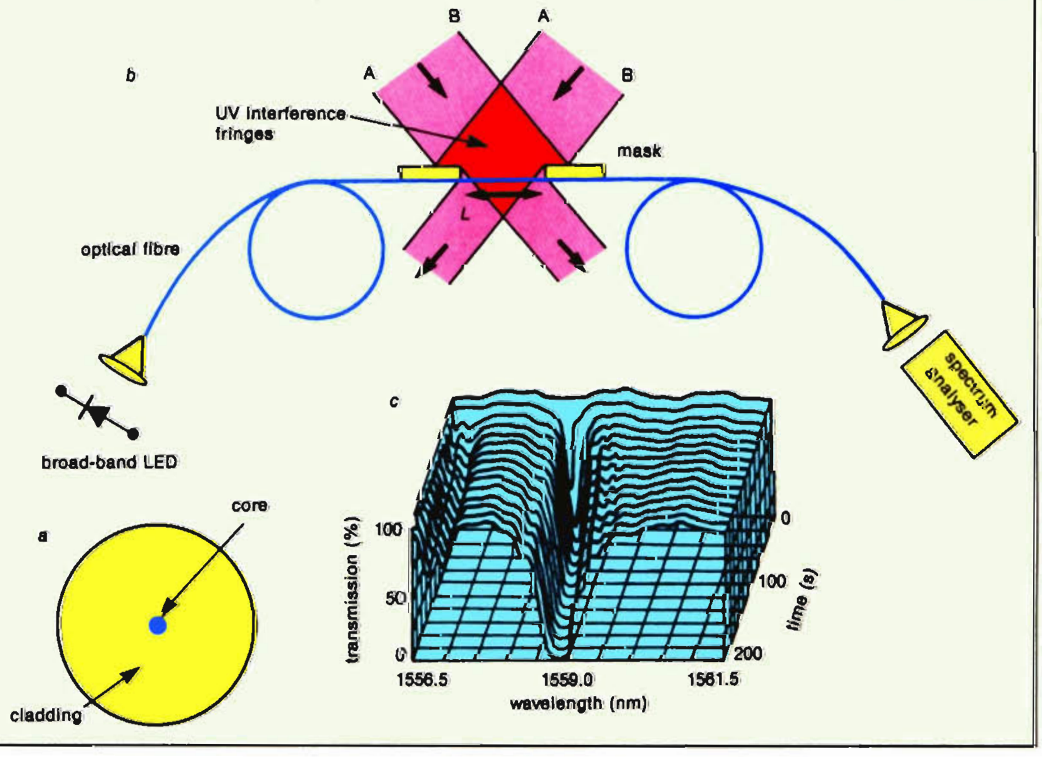
MIRRORS play a crucial role in any laser or optics system. But, until recently, mirrors made directly in optical fibre – and hence ideal for integration into fibre-based telecommunication, laser and sensor systems – have not been available, limiting progress in a whole range of optical fibre technologies.

Mirrors are one of a family of optical components (including also filters and couplers) that are chiefly characterised by their performance as a function of wavelength. One attractive way to make a fibre behave like a mirror with a precisely controlled reflectivity is to induce a periodic refractive index distribution along its length – in other words, to set up a Bragg grating in the fibre. The grating period and length, together with the strength of the modulation of the refractive index, determine whether the grating has a high or low reflectivity over a wide or narrow range of wavelengths – that is, whether it acts as a wavelength division multiplexer in telecommunications, a narrow-band high-reflectance mirror in laser or sensor applications, or a wavelength-selective filter removing unwanted laser frequencies ("tap") in fibre amplifiers.

The first gratings were made using a complicated multi-step process (involving side-polishing, photoresist processing, holographic exposure and reactive ion-beam etching) that took two days and had low success rates. Within the past year, groups worldwide have achieved breakthroughs in direct optical inscription of high-quality gratings into the core glass by interferometric exposure to ultraviolet (UV) laser light. Gratings with a wide range of bandwidths and reflectivities can be formed in times between 20 ns (the duration of a 248 nm excimer laser pulse) to a few minutes. These gratings are low-loss in-line fibre devices that can be written into the core non-invasively when and where desired, offering narrow-band wavelength selection to precise specifications.

Optical fibres

Optical fibres have revolutionised global telecommunications, making possible the high-quality, high-capacity transoceanic telephone links (without the echo caused by the use of satellites) that are now taken for granted. What



1 (*a*) Structure of a typical single-mode fibre. (*b*) The UV inscription process. The two sides, A and B, of the interfering beams must coincide at the fibre. "Blazed gratings", which couple (or "tap") light from the core into the cladding with variable efficiency, can be produced by tilting the fibre relative to the fringes. (*c*) Evolution with time of the transmission spectrum of a Type I grating as a function of wavelength under multiple pulse exposure – the growth of grating strength with time is monitored using a broad-band LED and an optical spectrum analyser. Almost 100% reflectivity at 1559 nm can be seen. The shift of the minimum with time can also be seen

exactly is an optical fibre? It is a hair-thin thread of *cladding* glass (~125 μm in diameter) that contains at its centre an even thinner *core* of diameter 1–10 μm where the refractive index is raised slightly (figure 1*a*). The core/cladding combination acts as a converging lens, permitting normal beam diffraction to be balanced out by focusing; at the correct guiding condition, these two effects exactly cancel, and light is trapped in a guided mode that can travel down tens of kilometres of fibre without strong attenuation. This guided mode possesses a constant effective refractive index n_m along the fibre (n_m lies between the core and the cladding indices), and thus a precisely defined wavelength λ/n_m, where λ is the *in vacuo* wavelength.

The cladding is normally made from pure fused silica, and the core from doped silica containing a few mol% of germania; other dopants, such as phosphorus, can be used, but germanium is the most common. Two windows of extra-low absorption occur in germanosilicate fibre at 1.3 and 1.55 μm. At these wavelengths, the core material of a state-of-the-art communications fibre is so transparent that, if it replaced sea-water, a passenger on a ship sailing over the Marianas Trench in the Pacific could easily see (using an infrared viewer) the ocean floor some 11 km below. This extreme transparency makes all the more unexpected – and serendipitous – the discovery that when germanosilicate glass is exposed to UV laser light in the 240–260 nm band, it develops large permanent changes in refractive index which can be measured out into the infrared. Still more fortuitously, the index changes obtained are the highest that have yet been observed in any glass. These features make germanosilicate glass a perfect medium for "holographic" production of fibre gratings for use at infrared wavelengths.

Glass, as mirrors, windows, spectacles and wine glasses etc, has been known for thousands of years to be transparent to visible radiation. This is because neither electronic nor molecular resonances exist in the visible range of frequencies. In the infrared (beyond ~2 μm), molecular resonances block the transmission of radiation, which is why greenhouses operate so well. In the UV, radiation gets progressively more and more cut-off at wavelengths below 300 nm. At these shorter wavelengths, the photon energy is much higher, and it is the electronic bonds that display resonances (the Si–O absorption edge begins just below 200 nm, and some defect centre bands occur between 200–300 nm).

The absorption of a UV photon acts like a precise cut with a scalpel blade, severing only those bonds that are at resonance. The electron released in this process is either retrapped at its old site, or drifts away and is trapped at another site in the glass. In the second case, the absorption spectrum changes more or less permanently (depending on the depth of the trap), causing refractive index changes that approach an asymptotic value at longer wavelengths. In general, several different electronic absorption bands will participate in this process, each adding its own contribution to the overall change in refractive index.

Grating diffraction

A diffraction grating with a refractive index profile

$$n(\mathbf{r}) = n_0 + n_1 \cos \mathbf{K}.\mathbf{r}, \qquad (1)$$

where n_0 is the average index, n_1 is the amplitude of the grating (typically 10^{-5}–10^{-2}) and $\mathbf{r}$ is the distance along the fibre, permits light with wavevector $\mathbf{k}_i$ to be scattered in a direction given by the diffracted wavevector $\mathbf{k}_d = \mathbf{k}_i - \mathbf{K}$. Here $\mathbf{K}$ is the grating vector; its direction is normal to the grating planes and it has a magnitude $2\pi/\Lambda$, where Λ is the grating spacing. If the diffracted wavevector matches that of a free wave at the incident frequency, strong Bragg diffraction into the $\mathbf{k}_d$ direction occurs; if not, the effectiveness of diffraction is reduced. The value of Λ needed to reflect light guided in a single-mode fibre core is given by the first-order Bragg condition:

$$\Lambda = \lambda_B / 2n_m \qquad (2)$$

where λ_B is the Bragg wavelength and n_m is the effective refractive index of the core mode. The reflectivity is given by

$$\eta = \tanh^2(\pi n_1 L / \lambda_B) \qquad (3)$$

where L is the grating length. The grating strength (or amplitude), n_1, is a function of how long the fibre has been exposed to UV illumination. The bandwidth of Bragg reflection depends on two things: the number, N, of grating planes, and the strength of the index modulation n_1. A certain proportion of the incident light is reflected at each grating plane; if the Bragg condition is not satisfied, then the wavelets reflected at each subsequent plane become progressively more and more out-of-phase ("dephased"); if, however, the grating strength is sufficient, a substantial proportion of the incident power can be reflected before dephasing becomes important. If it is too weak, then very little power is reflected before dephasing sets in. The balance between the dephasing length, the physical length of the grating, and the length (at exact phase-matching) needed for substantial reflection determines the bandwidth of the Bragg reflection. A general expression for the approximate full-width-half-maximum (FWHM) bandwidth of a grating is

$$\Delta\lambda/\lambda_B = \Delta\nu/\nu_B = s\sqrt{(n_1/2n_0)^2 + (1/N)^2} \qquad (4)$$

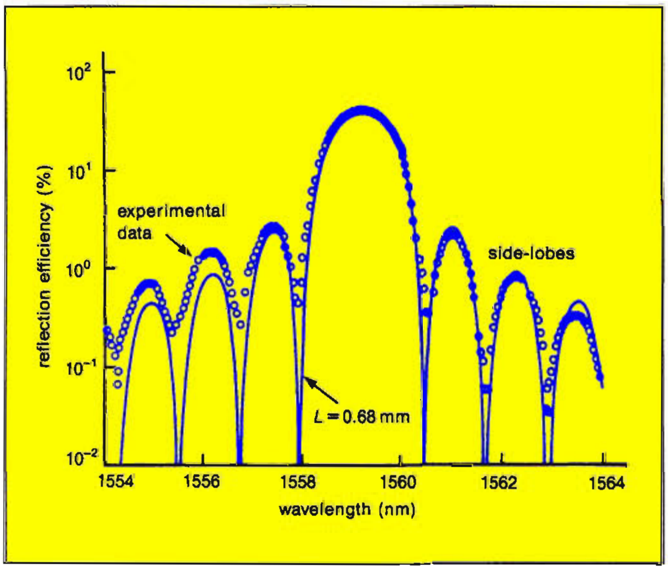
where ν_B is the Bragg frequency. The parameter s equals ~1 for strong gratings (with near 100% reflection) and ~0.5 for weak gratings. Multiple reflections to and fro between opposite ends of the grating region cause side-lobes to appear off-resonance; this is particularly noticeable for strong gratings (see figure 2).

Gratings in germanosilicate glass

In 1978 Ken Hill and colleagues at the Communications Research Centre, Ottawa, Canada, exposed fibres to narrow-band blue (488 nm) or green (514.5 nm) argon laser light and found that the fibres gradually "grew" a Bragg reflection grating. The process was initiated by interference between the incident light and the 4% light reflection from the end of the fibre. These first gratings were thus "self-organised" – they formed spontaneously, without human intervention. The mechanism remained somewhat mysterious for about a decade. It is now clear that two-photon absorption of the blue/green laser light, that is absorption of two photons to a higher-lying energy level, initiates the ionisation of oxygen-deficient bonds ("defects") whose absorption band is centred at 245 nm. The electrons released in this process are retrapped at other sites. The result is a refractive index change in the glass that remains after the laser light is blocked. Self-organised grating formation has remained a curiosity because it cannot be used to produce Bragg reflectors at other wavelengths (such as in the infrared), and in the blue/

green the gratings are intrinsically unstable owing to the continuing photosensitivity of the fibre. This causes the grating to continue to evolve during use as a Bragg reflector; if exposed to light of a different blue/green wavelength it can even disappear completely, i.e. be "bleached out".

The field did not progress until 1989, when Gerry Meltz and colleagues of United Technologies, East Hartford, Connecticut, proposed that fibre gratings could be formed by exposure through the cladding glass to two interfering beams of coherent UV light (figure 1*b*), thus exciting the 245 nm band directly by one-photon absorption. This suggestion has now borne fruit, and efficient gratings can now be produced with Bragg wavelengths from the visible to the infrared.



2 Measured reflection as a function of wavelength, on a logarithmic scale, for a grating written through a UV mask, producing a "top-hat" distribution of grating strength. n_1 = 0.000545, L = 0.68 mm (circles are data points, full curves a theoretical fit)

Crucial to the Meltz mechanism is the presence of oxygen deficiencies. These are common in optical fibres; they arise during the chemical vapour deposition formation process, and cause the formation of bonds like Si–Ge, Si–Si and Ge–Ge (normally there is a bridging oxygen). Since the absorption of photons at or near 245 nm causes breakage of these bonds, the theory (based on the Kramers–Kronig relationship between absorption and refractive index) predicts that the observed index change should be negative, not positive as measured. However, careful absorption measurements below 200 nm by Rob Atkins and colleagues at AT&T Bell Laboratories in New Jersey, US, have shown that the bleaching out of the 245 nm band is accompanied by the appearance of a strong additional absorption band below 200 nm. These measurements provide confirmation that a colour-centre defect model satisfactorily explains the index changes in the glass, as first proposed at Southampton by Duncan Hand and one of the authors in 1990.

Grating production with UV light

For operation at 1.55 μm, the wavelength of minimum attenuation in silica fibre and the preferred operating wavelength of long-haul telecommunication systems, a typical optical fibre has an effective index for the core of ~1.45, yielding (equation 2) a grating spacing, Λ, of ~500 nm. The challenge is thus to produce such fine-period structures in the core. Three techniques have been used: interferometry; replication using phase masks; and point-by-point writing.

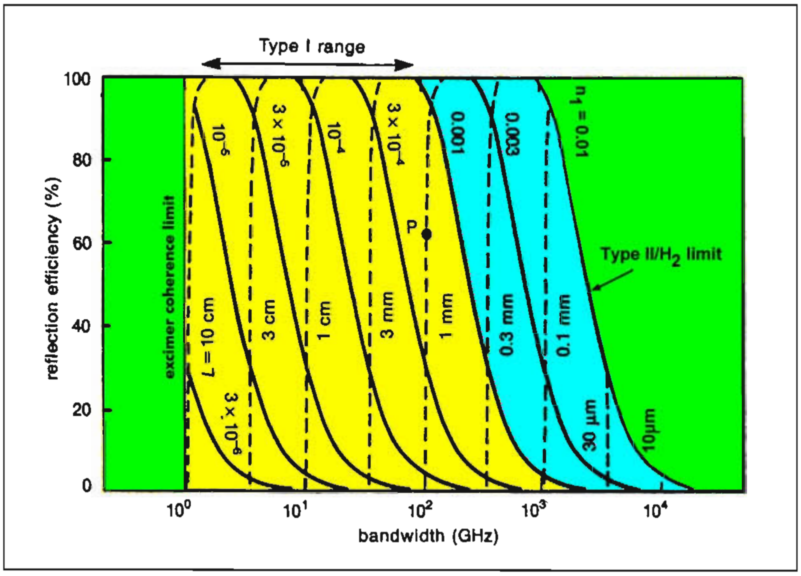
Although traditional excimer lasers deliver substantial powers, (several 100 mJ over 20 ns, i.e. peak powers of >5 MW), they have poor temporal and spatial coherence, making them unsuitable for interferometry. Improvements in laser design have, however, made coherence lengths of 25 mm possible, reasonable for such a system. While the transverse beam quality is still poor, i.e. the spatial coherence is low, this can be side-stepped by designing an interferometer in which the two beams undergo the same number of reflections before interfering at the fibre; with careful alignment, this eliminates the detrimental effects of spatial incoherence. Another promising technique, well known in holography, which does not suffer from stability or coherence problems, is the use of phase masks, as demonstrated by several groups worldwide. The third technique is point-by-point writing, pioneered by Bernard Malo and colleagues at the Communications Research Centre, Ottawa, in which each grating plane is produced separately by a focused single pulse from an excimer laser. Because of the need for precise control of the submicron-sized steps, the tight focusing required, and the many planes that need to be written, only rather short gratings, with Λ = 1.5 μm, have been written in this way so far.

Appropriate lasers include pulsed (20 ns) KrF excimer lasers at 248 nm, frequency-doubled argon lasers at 244 nm or 257 nm, frequency-quadrupled Nd:YAG or Nd:YLF lasers, and the laser used by Meltz – an excimer-pumped dye laser pumping a frequency-doubling crystal to produce tunable radiation between 243–250 nm.

Figure 1*b* shows the experimental set-up for producing fibre gratings. It also shows the measured evolution of the transmission spectrum of a fibre grating, plotted as a function of excimer pulse count. The excimer laser beam is split into two and recombined coherently at the core of the fibre. The nodes and antinodes of the interference pattern periodically modify the refractive index of the glass in the core of the fibre, gradually building up a Bragg grating. Each successive excimer pulse (repetition rate up to 80 Hz) contributes a little more to the grating strength, while at the same time causing the average index to rise; the result is that the transmission minimum creeps slowly to longer wavelengths as the grating strength rises. This "multiple-pulse" technique allows precise control of the grating properties during inscription; it has the disadvantage that displacements (produced by mechanical vibration or thermal drift) as small as 100 nm in the positions of the mirrors, beam splitters and mounts in the interferometer can cause the fringe pattern to move, washing out the forming grating. This problem of "path length drift" can be avoided if the pulse energy is increased, when (as first shown by Charles Askins and colleagues at the Naval Research Laboratory, Washington DC) weak gratings can be produced by a single excimer pulse. The gratings formed by this technique are termed "Type I" (continuous-wave lasers can also be used).

Another way

At Southampton we have discovered a new formation mechanism for fibre gratings, based on actual – and precisely limited – physical damage to the fibre core. The onset of these "Type II" gratings is marked by a 1000× increase in the index change induced by a single pulse, resulting from only a two-fold increase in 248 nm pulse energy from 20 to 40 mJ. Although the origins of the process are not fully understood, it seems likely that both two-stage and two-photon absorption play a role (the first being initiated by high single-photon absorption at 248 nm – several dBs across the fibre core), exciting electrons into the conduction band of silica where (under the influence of the UV light) they seed the formation of a "free" electron plasma. This would then produce an abrupt surge in UV absorption, and damage the glass. What is particularly impressive about this process is that ~100% reflecting gratings can be formed in just 20 ns. Type II gratings are thermally extremely stable (up to 800°C), making them useful for sensing applications in hostile environments and, unlike Type I gratings, they are not erased by green or blue light; this will make them important in visible fibre lasers. Type II gratings share many of the same features as the earlier etched-fibre gratings, but can be produced much more quickly.



3 The reflection efficiency and bandwidth that can be achieved simultaneously at 1.5 µm with state-of-the-art gratings (s in equation 4 is averaged at 0.5 across this diagram). L is the length of the grating and n_1 is the grating strength. This graph can be used as a parameter design plot for gratings that lie within the experimentally accessible ranges. For example, if a bandwidth of 100 GHz and a reflection efficiency of 60% was needed (point P on the diagram), the grating would need to be 1 mm long and have a strength of 0.0006. The limits are imposed by the coherence length of the excimer laser and the maximum index change attainable. If a certain bandwidth is required, then the best performance occurs when the reflection efficiency is just strong enough for the application; too high an efficiency produces unwanted strong sidelobes. The yellow region represents conventional Type I gratings, the blue region type II and hydrogenated Type I gratings. The green region represents gratings that cannot be realised experimentally

The ability to write gratings with a single excimer pulse is of great practical importance for large-scale grating production during fibre fabrication. The fibre-pulling process involves heating the end of a glass preform rod (diameter ~1 cm) until it is soft, and then pulling it into fibre (diameter ~0.1 mm) at typical speeds of 1 m s^{-1}. Between leaving the furnace and being rolled on a drum, the fibre is "sleeved" with polymer to protect it from water vapour and increase its long-term durability and strength. During a single excimer pulse, the fibre moves only 20 nm, and since required grating periods range from 200–550 nm, 100% reflecting gratings can be written in the fibre core *while the fibre is being pulled* and before it is sleeved. This technological advance was demonstrated for the first time in July 1993 by Liang Dong and colleagues at Southampton.

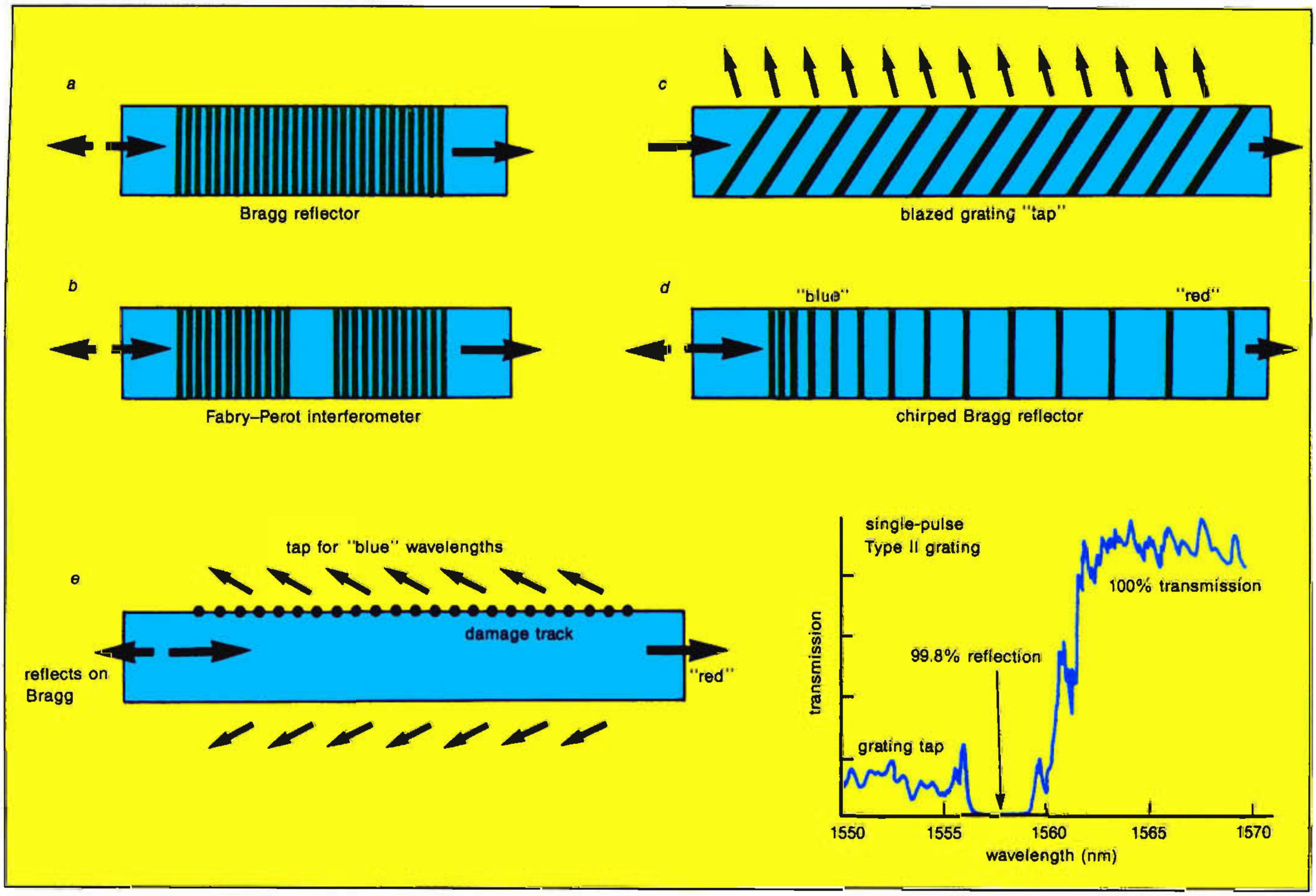
Further improvement of the fibre's photosensitivity can be achieved by using hydrogen. This is under investigation by several groups worldwide, most recently by Paul Lemaire and colleagues at AT&T Bell Laboratories. Every "as pulled" germanosilicate fibre core is oxygen deficient to some extent, and it is these oxygen-deficient defects that cause the fibre's photosensitivity. The photosensitivity can, however, be enhanced a hundred fold by soaking the fibre in hydrogen gas at 200 atmospheres and room temperature. Exposure in the UV interferometer then initiates chemical reduction of the glass, greatly increasing the index change which can be obtained. Type I index changes as high as 0.01 (which is of the same order as the difference between the core and cladding indices) have been achieved in this way. The technique can treat short lengths of fibre, leaving the rest unaffected, and can produce strong gratings in any fibre containing germanium, even when the fibre does not initially exhibit strong photosensitivity (as in standard telecommunications fibre).

Applications

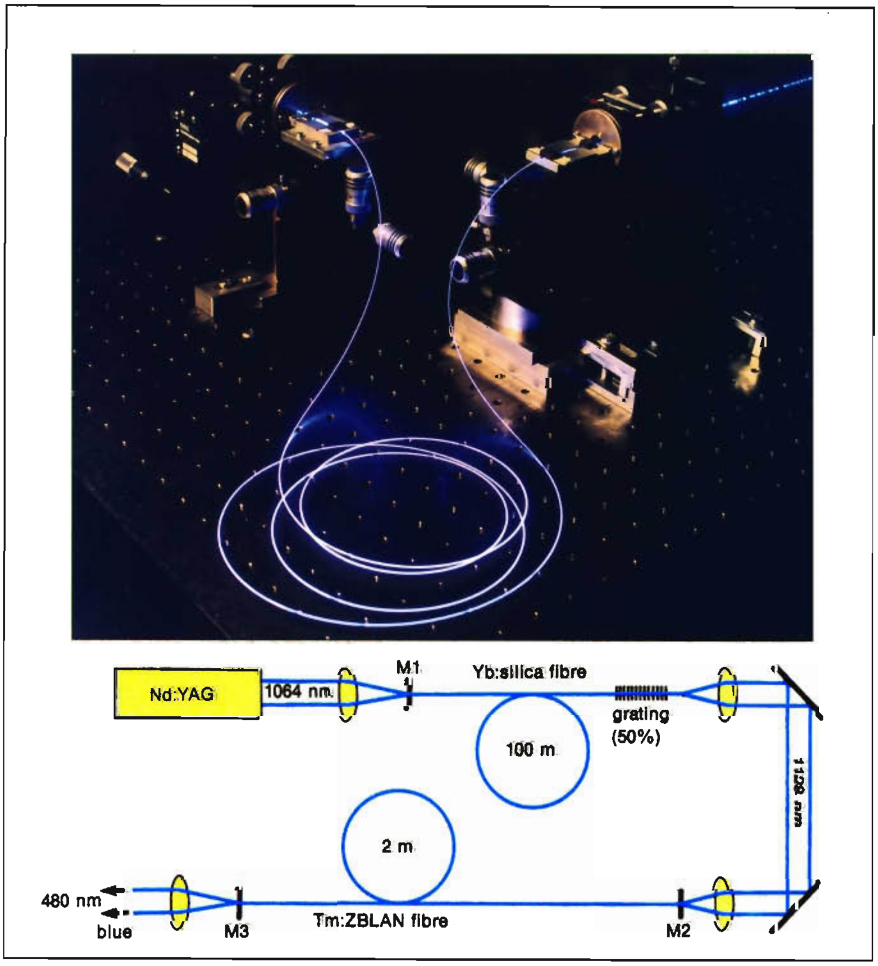
In conventional optics, mirrors of controlled bandwidth and reflection efficiency are produced by multilayer dielectric coatings or thin metal layers. These techniques are difficult to implement in fibre optics, and are only convenient if broad bandwidths of reflection are required. For maximum practical usefulness, in-line fibre mirrors need to offer a much wider range of reflection efficiencies and bandwidths. State-of-the-art fibre gratings satisfy these requirements to a remarkable degree, offering great design flexibility. Bandwidths between 6 GHz and 2 THz at 1.5 µm, and reflectivities up to 100% are possible by varying the length of the grating and the induced refractive index change, though not always at the same time (figure 3).

Applications can therefore range from narrow-bandwidth Type I filters for wavelength division multiplexing (used to combine or separate telecommunications signals) to high-bandwidth high-reflectivity mirrors for fibre lasers and sensors. Generally, Type I gratings do not couple or "tap" out shorter wavelengths into the fibre cladding, whereas Type II gratings do (figure 4). This makes both of them useful, although in different contexts. Type I mirrors provide narrow-band feedback (and single-frequency operation) in a conventional fibre laser and allow the lasing cavity to be pumped without "tapping out" the pump power from the core. Type II gratings, distributed throughout the lasing region of an optical amplifier, can be designed to tap out unwanted amplified spontaneous emission at shorter wavelengths.

Multiple Type I side-tap fibre gratings have been used by Raman Kashyap and colleagues at British Telecom, Ipswich, UK, to flatten the gain spectrum of erbium-doped fibre amplifiers. This is important in fibre communications that use several signals at different wavelengths. Conventional lasers with simple broad-band mirrors oscillate at the wavelength that coincides with the peak in the gain band for the laser material; if these broad-band mirrors are replaced with narrow-band Type I gratings, the laser can be forced to oscillate at wavelengths towards the edges (the "wings") of the gain band, which effectively suppresses oscillation at the centre-band wavelength. An



▲**4** Range of fibre devices incorporating gratings. Only the single-mode core is depicted; it is surrounded by cladding glass, and for operation at 1.55 μm has a typical diameter of ~5 μm. (*a*) Bragg reflector. (*b*) Fabry–Perot interferometer in which the light resonates between the two reflectors. (*c*) Blazed grating tap. (*d*) Chirped Bragg reflector. In each of these four Type I gratings the three-dimensional Bragg condition is satisfied by the incident mode and the diffracted light. The grating pitch (spacing between the planes) for reflection at this wavelength is ~500 nm. (*e*) Type II damage gratings (left) are localised on one side of the core, which lets them act as effective grating taps; Type II experimental transmission spectrum (right)



◀**5** 480 nm blue up-conversion laser in thulium-doped ZBLAN (zirconium barium lanthanum aluminium sodium fluoride) fibre; the blue-glowing fibre coiled on the bench is the laser, emitting a blue light beam from the top right-hand corner. It is pumped by an ytterbium-doped silica fibre laser (itself pumped at 1064 nm) containing a fibre grating to force it to oscillate at 1128 nm (its centre of gain is at 1100 nm). Mirror M1 transmits 1064 nm and reflects 1128 nm; M2 transmits 1128 nm and reflects 480 nm, and M3 reflects 70% at 480 nm example is the blue up-conversion fibre laser system developed at Southampton by Colin Mackechnie and David Hanna, shown in figure 5.

Many non-laser applications also exist. If the gratings are chirped (see figure 4) so that higher or lower frequencies travel further into the grating before being reflected, chromatic dispersion of short pulses in long-distance communications systems can be compensated for. Since the Bragg wavelength is a sensitive function of temperature, pressure and strain, narrow-band Type I gratings are important in quasi-distributed fibre sensing, for example in continuous monitoring of strain in supertankers to provide early warning of crack formation. And further – as yet undiscovered – combinations of gratings and existing fibre components are sure to lead to a whole range of more elaborate and unique grating-based devices.

A promising future

Direct interferometric exposure of germanosilicate core glass to UV light is perhaps the easiest and best route to grating formation known in any material; no post-processing, or special preparation, of the glass is needed. The technique is entirely non-invasive, and mass production during fibre pulling is possible. In addition to offering unmatched transparency, optical fibres can provide efficient lasers and amplifiers at many wavelengths, including the important communications window at 1.55 μm, and glass fibre electro-optic modulators for communications systems may soon be available. Fibre gratings are the latest addition to an already impressive portfolio of fibre devices, formed in that wonderfully versatile material – silica.

Further reading

J-L Archambault, L Reekie and P StJ Russell 1993 100% reflectivity Bragg reflectors produced in optical fibres by single excimer laser pulses *Electron. Lett.* 29 453–454

L Dong, J-L Archambault, L Reekie, P StJ Russell and D N Payne 1993 Single pulse Bragg gratings written during fibre drawing *Electron. Lett.* 29 1577–1578

D P Hand and P StJ Russell 1990 Photoinduced refractive index changes in germanosilicate fibres *Opt. Lett.* 15 144–146

A Kamal, S E Kanellopoulos, J-L Archambault, P StJ Russell, V A Handerek and A J Rogers 1992 Holographically-written reflective polarisation filters in single-mode optical fibres *Opt. Lett.* 17 1189–1191

R Kashyap, R Wyatt and P F McKee 1993 Wavelength-flattened saturated erbium amplifier using multiple side-tap Bragg gratings *Electron. Lett.* 29 1025–1026

P J Lemaire, R M Atkins, V Mizrahi and W A Reed 1993 High pressure H_2 loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO_2 doped optical fibres *Electron. Lett.* 29 1191–1193

B Malo, K O Hill, D C Johnson and J Albert 1993 Point-by-point fabrication of microBragg gratings in photosensitive fibre using single excimer pulse refractive index modification techniques *Electron. Lett.* 29 1668–1669

G Meltz, W Morey and W H Glenn 1989 Formation of Bragg gratings in optical fibres by a transverse holographic method *Opt. Lett.* 14 823–825

W Lenth and R M MacFarlane 1992 Up-conversion lasers *Optics and Photonics News* 3 8–15

M G Sceats, G R Atkins and S B Poole 1993 Photolytic index changes in optical fibres *Ann. Rev. Mat. Sci.* 23 381–410

Philip St J Russell, Jean-Luc Archambault and Laurence Reekie are in the Optoelectronics Research Centre, University of Southampton, Southampton SO9 5NH, UK