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Optical waveguide components in organic photochromic materials

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SUMMARY
The principles and techniques for preparing and using photochromic waveguide passive components for fibre optics are described. The sandwiched layer is considered to have a robust format in which fibre-to-waveguide alignment is fairly easy and reliable.

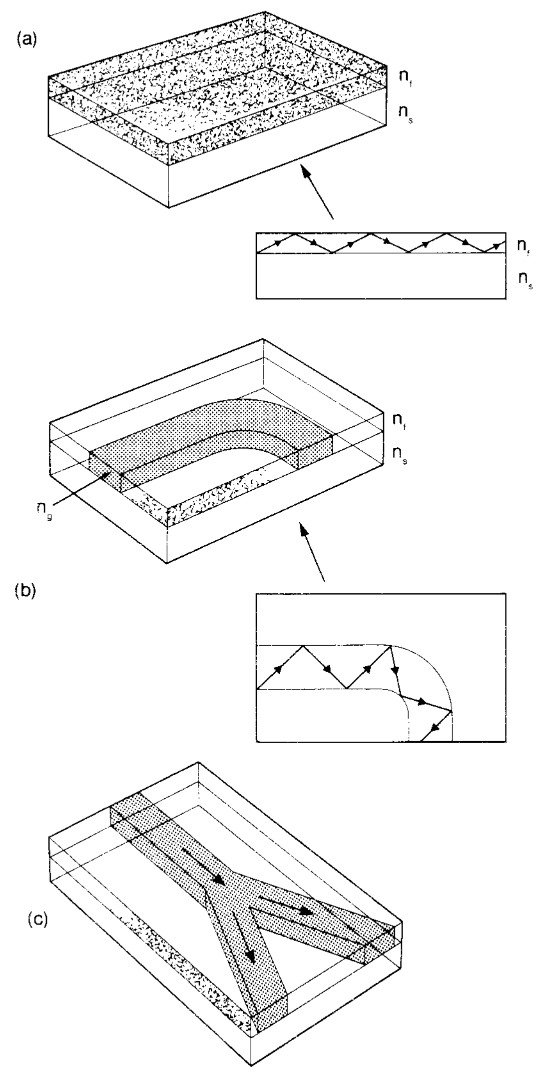
1 Introduction

The transmission of signals by light guided by fibre-optic waveguides is rapidly evolving into a major telecommunications technology. Light is modulated and injected into glass fibres of circular cross-section, comprising a central core region of refractive index higher than that of the surrounding cladding layer: the light is constrained and guided by the core. First-generation systems utilize multimode fibre in which the core diameter is relatively large, typically 60 or 70 times the wavelength of light. In such systems, the attendant passive components such as couplers, power dividers, wavelength filters and connectors may be constructed using miniature versions of familiar bulk optical components including lenses, prisms and diffraction gratings. However, the enormous potential bandwidth available from monomode fibres, wherein the core diameter is reduced to the order of 6 to 8 wavelengths, typically, was recognized more than ten years ago. At that time suitable light sources operated at wavelengths less than 1 μm and the small diameter of the corresponding monomode fibre core was seen to present problems too severe for component manufacture and alignment.

The impetus for development of practical monomode systems largely came about in 1976 when fibre transmission losses of 0·47 dB/km were reported at 1·3 μm wavelength. Three years later the loss figure was further reduced to 0·2 dB/km by employing a wavelength of 1·55 μm. This raised the possibility of repeaterless transmission of 10^9 bits per second of digital information over distances of a few tens of kilometres, which was sufficiently attractive to stimulate the rapid subsequent development of suitable light sources and detectors.

Implementation of practical monomode systems at these longer wavelengths is dependent, of course, on the development of a range of active and passive components, just as in the multimode case. The smaller fibre core diameter, however, implies that simply scaling the equivalent multimode components is not usually practical due to stringent alignment tolerances. One approach to monomode component design that has the potential to

Fig. 1. Optical waveguides, (a) Planar waveguide; (b) curved stripe waveguide; (c) Y-junction branching stripe waveguide.



circumvent many of the problems is based on the concept of integrated optics, and the role of photochromic optical waveguides falls within this category.

The principle underlying all integrated optics is that a thin layer of a dielectric supported by a substrate of lower refractive index can constrain light: the similarity to optical fibre propagation is obvious. Figure 1(a) illustrates the case wherein a ray of light is confined within a planar, thin film of refractive index n_f on a substrate of index n_s with n_f greater than n_s. Confinement is by total internal reflection at the film-substrate and film air-space boundaries. Figure 1(b) shows the concept taken one step further. In this case, a narrow stripe of material of refractive index n_g, greater than n_f, forms a waveguide which permits the additional, confinement of light in the dimension transverse to the direction of propagation by total internal reflection at the boundary between the regions having refractive indices n_g and n_f. In this way light may be constrained to follow, for example, the curved path of the stripe waveguide. In another example the waveguide may be formed into a Y-shaped junction as shown in Fig. 1(c) causing the incident light energy to divide between the two arms.

The example of Fig. 1(c) illustrates one conceptually simple application of integrated optical waveguide techniques to fibre optics. If a means of rigid, efficient coupling between fibres and stripe waveguides is devised, the Y-junction may be designed to function as a 3-dB power coupler, dividing the input light energy from one fibre equally between two output fibres. The principle may be extended to components providing a number of outputs from a single input, and many other configurations of greater complexity.

In addition to the signal routeing components based on the stripe waveguide principles discussed above, many other purely passive functions may be implemented in integrated optical form. In particular, Bragg diffraction of a guided light beam by a grating within the waveguide can be used to deflect or filter the beam, or couple the light out of the waveguide. The photochromic system to be described is ideally suited to the fabrication of such structures, and grating applications are considered in detail later.

The integrated optics approach to components fabrication has the obvious attraction that the several parts of a more complex component may be laid down in permanent optical alignment on a single substrate. Most of the relevant thin film fabrication principles have been extensively developed for the electronics industry. For the majority of waveguide materials systems that have been—and are now—considered, many processing steps are required to transfer the desired pattern into its final component form. Each step is a potential source of degradation, and the more that are required the lower the yield is likely to be. The system described here, based on novel organic photochromic materials is capable of producing complex patterns, containing very fine geometrical detail, in a one-stage pattern-delineation process. Waveguide components are formed simply by exposure to light. No subsequent processing is employed, leading to considerable advantages in terms of simplicity and cost. In the following Sections, the relevant photochromic material properties are discussed, followed by descriptions of photochromic components utilizing stripe waveguides and gratings. Fabrication details are given, and the important aspect of fibre-waveguide coupling described.

2 The Photochromic Materials

A photochromic material is characterized by its ability to undergo reversible transformation between two different

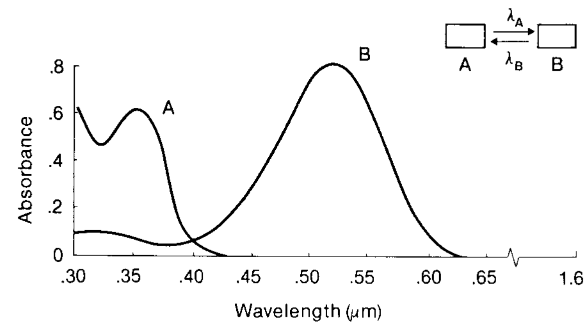


Fig. 2. Absorption spectra of the photochromic compound 540.

chemical forms in response to irradiation with light. The two forms possess widely separated, strong absorption bands located in the ultraviolet-visible spectrum. Figure 2 shows the absorption spectra of the two states A and B of the Plessey photochromic designated type 540.† Absorption of light in the ultraviolet-blue range by material in state A converts it to State B, while the reversible transformation from B to A is induced by absorption of visible light in the wavelength range 450–550 nm. In contrast with the majority of established organic photochromic systems this material in common with others in the series, does not undergo thermal transformation from B back to A. All photochromics described here are derivatives of dimethyl succinic anhydride referred to generically as fulgides. The photo-chemistry of these materials was discussed in the A.C.R.C. Annual Review 1977. For optical waveguide use, fulgides are deposited in thin films as solid solutions in selected polymer matrix materials.

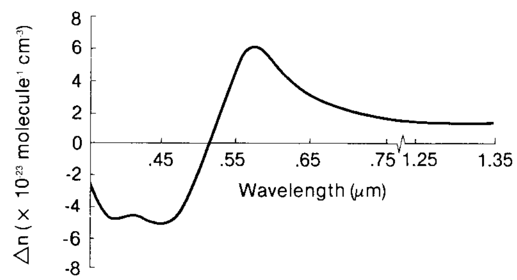


Fig. 3. The difference in refractive index. Δn, between the two states A and B of photochromic 540 in a PMMA matrix, as a function of wavelength.

Associated with the absorption bands is a refractive index difference, Δn, between material in each of the two states. Figure 3 shows the refractive index change available from 540 in a poly(methyl methacrylate) matrix. It is apparent that an optical waveguide can be produced in this material by selectively converting a strip of the film to the higher refractive index state, and the techniques for accomplishing this with the necessary precision are described in the following Section. The resulting waveguide must, of course be employed to carry light at wavelengths well outside the photochromic absorption band to avoid erasure of the higher index state. In practice, wavelengths longer than about 1 μm are required, and the system is ideally suited for the longer wavelength, 1·3–1·6 μm fibre optic applications described.

† Type 540 material is E.α 2,5-dimethyl-3-furylethylidene-isopropylidene succinic anhydride: to ease subsequent discussion we shall continue to refer to it by its type number.

In contrast with, for example, conventional photography, the photochromic response to incident illumination is non-multiplicative and the sensitivity relatively low, being similar to typical high-resolution positive photoresists. Each molecule undergoing a change of state is required to absorb one photon of the incident radiation. The discrete molecular mature of the process provides a resolution capability that, in practice, is limited only by the wavelength of light and quality of the exposure system optics.

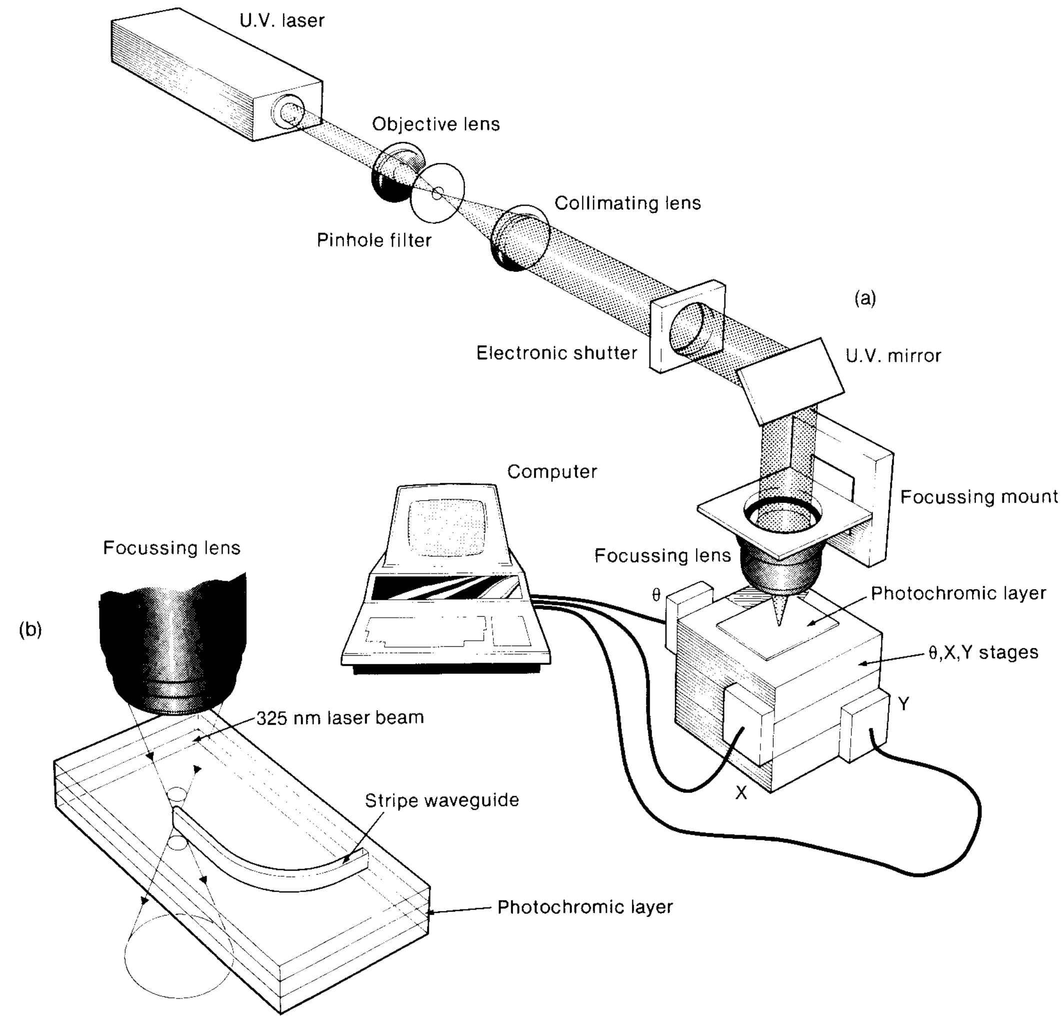
3 Optical Waveguides in Photochromic Layers

A photochromic optical waveguide component is produced by selectively converting areas of a thin layer of the material to the higher refractive index state. In order that the resulting waveguides may exhibit low propagation losses, it is essential that the matrix materials have negligible absorption at the wavelengths of interest and that deposition techniques exist for producing optically flat waveguide layer surfaces. Small deviations from surface flatness, less than one hundredth of a wavelength, can be significant and act as scattering centres if the pitch of the deviations approaches the wavelength. An additional requirement of the matrix material is that it should be capable of forming stable solid solutions with photochromics over a wide range of concentrations. A number of polymer materials have been identified as possessing the requisite characteristics and have been utilized in the work described here. They may be divided into two classes distinguished by the deposition techniques.

The first group comprises materials that are deposited as thin layers from liquid solutions; these are largely acrylic plastics. Photochromic and polymer are dissolved in the desired proportions in a low-volatility organic solvent and applied to a precleaned substrate by flow-coating, spin-coating or roller-coating. Although each has provided satisfactory photochromic layers, the flow-coating technique is favoured, providing controllable uniformity over a large area by simple means. In this technique the liquid solution is filtered and applied to a horizontal substrate which is then rotated to a vertical position where it is held for a predetermined time related to the materials and desired layer thickness. It is then returned to the horizontal and the solvent allowed to evaporate under controlled conditions. Photochromic layers only a few microns thick produced by this simple technique exhibit excellent thickness uniformity over 80% of the coated surface area. Guided-wave propagation losses in the planar layers do not exceed 1 $dB.cm^{-1}$. Matrix materials providing a range of refractive indices have been used to produce the waveguide films for this work: they are poly(methyl methacrylate) (PMMA), poly(cyclohexyl methacrylate) (PCHMA) and poly(benzyl methacrylate). Suitable substrates are glass, silica and PMMA.

The second group comprises thermoplastic materials in which the photochromic compound is dissolved. A thin layer is produced by compressing the molten solution

Fig. 4. (a) Arrangement of computer-controlled exposure of photochromic layers to produce waveguide patterns. (b) Stripe waveguide exposure.



between glass substrates. Air trapped in the sandwiched layer is removed by evacuation. The layer has excellent thickness uniformity and the structure is mechanically robust, with the photochromic layers protected on both surfaces. In the work reported here, the alkyl resin poly(ethylene orthophthalate) has been used as the matrix.

Prior to defining a waveguide pattern the photochromic layer in either format is converted to the lower refractive index state. It is then positioned on the sample platform of the exposure apparatus, illustrated schematically in Fig. 4(a). Here, an ultra-violet laser beam is brought to a focus in the photochromic layer, as shown in Fig. 4(b), and the sample moved through the focused beam to define the stripe waveguide pattern by conversion to the higher index state. The helium-cadmium laser emits 2 mW of light at 325 nm wavelength and is carefully adjusted to maintain its output in the fundamental mode, producing a Gaussian intensity profile.

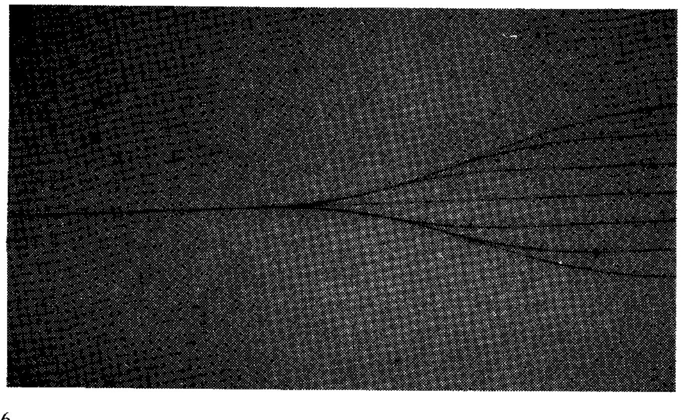
The optical system spatially filters, expands and collimates the beam to a diameter determined by the focal length of the collimating lens. Adjustment of the expanded beam diameter prior to the final focusing lens may be used to select the final spot size, and, hence, the width of the stripe produced. The focusing lens is a microscope objective—typically ×10 magnification—which is mounted on an electrically driven moving coil positioner giving translation normal to the waveguide plane. Through this adjustment, fine positioning of the beam waist in the sample depth may be achieved and for some applications, such as producing waveguide horns and similarly tapered structures, smooth defocus may be introduced during the exposure. Final control of the exposure is accomplished by varying the speed of motion of the sample platform.

The sample platform is mounted on two orthogonal translation stages and one rotation stage, each stepper-motor driven with increments of 1 μm and 15 arc seconds, respectively. The absolute position of the platform is determined, when required, by means of capacitive compression probes. The stepper-motors are driven under computer control which permits a wide range of waveguide patterns to be accurately written and more complex junctions reliably reproduced. The system is flexible, permitting rapid implementation of design changes. Figure 5 shows an example of a photochromic waveguide pattern produced on this apparatus.

Although photochromic waveguide components are intended to be used with light coupled into the waveguide directly from a fibre, as described later, evaluation is routinely performed on open layers by employing an experimentally more convenient arrangement, depicted in Fig. 6. Light is incident on a glass prism, of refractive index greater than that of the waveguide, surmounting the waveguide and separated from it by an air gap of less than a wavelength. Total internal reflection at the prism base is frustrated by the close proximity of the waveguide, and light leaks through the gap into this layer. The angle θ (Fig. 6) can be varied to a point at which the leaking light satisfies a phase-matching condition for guided propagation, when the incident beam is strongly coupled into the waveguide. Slight adjustment of the incident beam angle normal to the plane of the diagram is required to optimize the power transfer to a stripe waveguide. Figure 7 shows a portion of a prism-coupled guided beam in a curved photochromic 540/PMMA waveguide on a silica substrate. The guided wavelength in this case was 799 nm to facilitate photography.

Figure 8 shows a versatile implementation of photochromic waveguide techniques, where the photochromic layer is deposited on a glass substrate of graded refractive index. The substrate is produced by ion-exchange in glass, a technique now widely used to produce optical waveguides with very low loss. (When the surface of a homogeneous glass substrate is immersed in a molten silver salt, sodium ions diffuse from the glass to be replaced by silver ions diffusing from the melt.) The resulting layer has a graduation of refractive index from the maximum value of the surface to the minimum value of the bulk, undiffused glass at a characteristic depth. By proper choice of the refractive indices of the photo-

Fig. 5. Example of a complex waveguide pattern produced by laser beam writing in a photochromic layer.



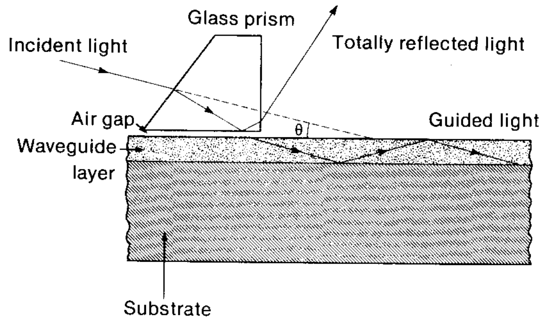


Fig. 6. Prism-coupling to a waveguide.

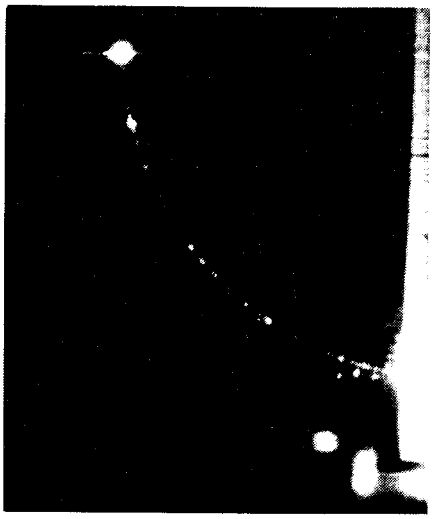


Fig. 7. A photochromic stripe optical waveguide. Light was coupled from a laser into the waveguide by the prism-coupling technique illustrated in Fig. 6. (The edge of the prism is just visible at the right of the photograph).

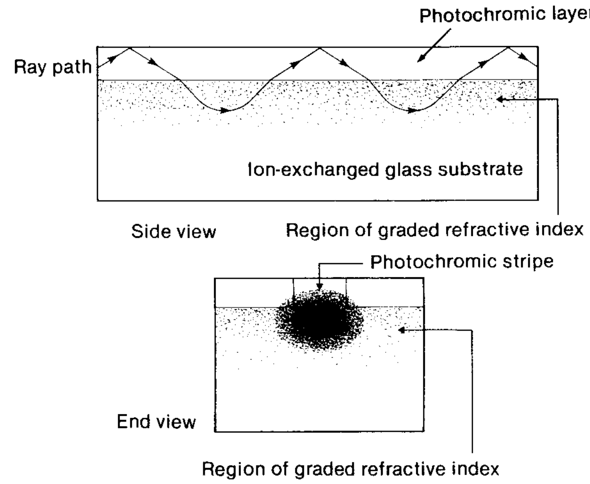


Fig. 8. Composite stripe waveguide formed by a photochromic overlayer on an ion-exchanged glass substrate, showing guided mode cross-section.

chromic, the glass and the diffused layer, a large fraction of the energy of radiation propagated in the composite structure will be in the diffused layer but the path followed by the radiation will still be defined by the waveguide stripe in the photochromic layer. This allows the depth of the effective light guide to be increased to the 8 to 10 µm needed for efficient coupling to a fibre while maintaining the photochromic thickness of 2 to 3 µm. The use of a thinner photochromic layer greatly improves its optical surface quality and reduces the scattering losses due to imperfections in the boundaries of the stripe waveguides. It is also very much easier to control the depth profile of the induced refractive index change in a thinner layer.

Stripe waveguides are produced in this configuration by exactly the same procedure as previously described. The overlayer may have a greater or smaller refractive index than that at the graded layer surface, but the preferred structure uses a PCHMA matrix yielding an overlayer of slightly higher index, and, correspondingly, tighter confinement of the guided wave.

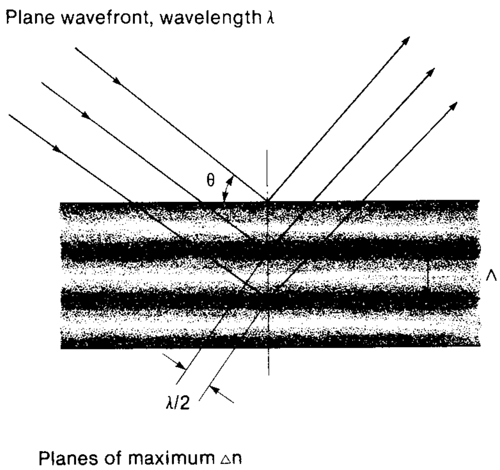
4 Gratings and Their Applications

Bragg diffraction at a periodic structure is well-known, particularly by association with X-ray studies on crystals and optical holography. Figure 9 represents the optical case of interest here: the periodic structure is produced by planes of alternating high and low refractive index. Light incident as a plane wave in a medium of refractive index n is strongly diffracted by the grating when the condition

$$2\Lambda\sin\theta = m\lambda \qquad (1)$$

is satisfied, where Λ is the grating period, θ the angle of incidence shown in Fig. 9, m an integer, and λ is the wavelength of the light in the medium. (Here, $\lambda=\lambda_0/n$, where λ_0 is the free-space wavelength.) Equation (1) describes the condition by which waves partially reflected from successive planes are phase matched and interfere constructively.

Fig. 9. Bragg diffraction by a periodic distribution of refractive index.



In Fig. 10 a guided light beam in a planar optical waveguide encounters a grating formed as a periodic perturbation of the waveguide refractive index. This beam undergoes Bragg diffraction when the guide wavelength, λ_g, satisfies the relation (1). When the grating planes are oriented at right angles to the waveguide boundaries and, hence, are normal to the plane of propagation, the diffracted beam may be directed out of the waveguide. The utilization of the latter configuration as a beam coupler is described later and the following discussion is concerned with guided, diffracted beams.

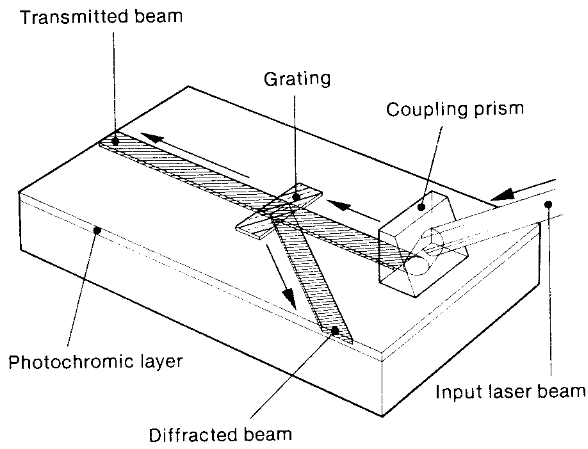


Fig. 10. Guided wave Bragg diffraction by a waveguide grating.

The strength, or efficiency, of the diffraction process increases to a maximum value with increasing difference between high and low refractive index values in the grating and with the length of the grating. In the absence of loss mechanisms—absorption, scattering and radiation—all of the incident power may be concentrated into the diffracted beam, resulting in a guided-wave beam deflector or mirror. Alternatively, by controlling the interaction efficiency an arbitrary fraction of the incident power may be diffracted, the rest remaining undeviated: this configuration finds application as a tapping coupler or beam splitter.

Planar photochromic waveguides obviously lend themselves to the fabrication of waveguide grating components, through the refractive index change available. However, in any typical application the period of the grating is usually only a fraction of 1 µm, and conventional optical lithography cannot be employed to produce the pattern. Instead the techniques of interference lithography are used, depicted in one arrangement in Fig. 11. Two collimated laser beams are brought together in the photochromic layer forming an interference pattern comprising parallel, equi-spaced, straight-line fringes. Exposure to this pattern produces a sinusoidal distribution of refractive index throughout the volume of the waveguide. The grating boundaries defining the length of

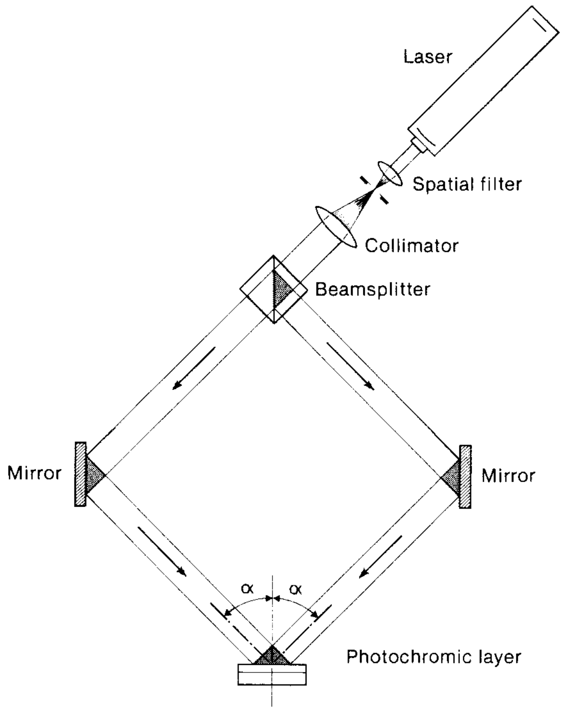


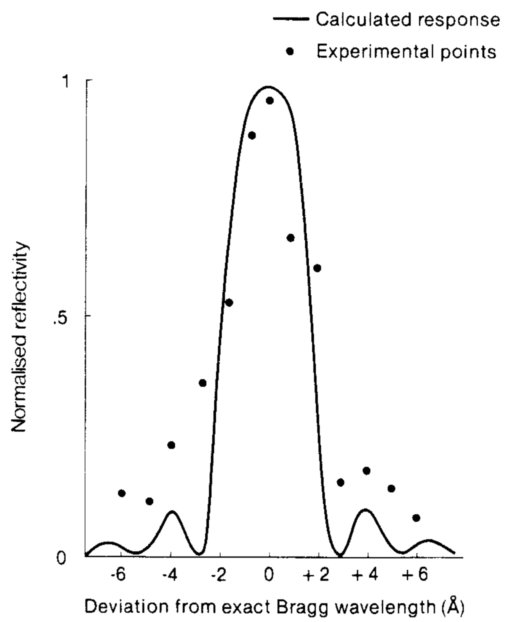
Fig. 11. Optical arrangement for fabrication of gratings in photochromic layers, by laser beam interference.

the interaction region, and hence the grating efficiency, are produced by a simple contact-exposure through a corresponding mask. Most commonly the grating boundaries are defined by pre-exposure to a low power ultraviolet lamp, converting a small area of the waveguide to the higher index state. The fringe pattern is subsequently produced by beams from an argon laser operating at 514·5 nm, near the photochrome absorption peak for the B→A state change. A typical photochromic waveguide grating is 0·2 to 2 mm long by a few millimetres wide. For a 90° beam deflector for radiation 1·3 μm wavelength, the grating period is of the order of 0·61 μm.

Bragg diffraction is highly wavelength-selective. At constant angle of incidence, the diffraction efficiency of a waveguide grating is a strong function of wavelength characterized by a bandwidth that can be extremely narrow. An exact mathematical description that covers all cases of interest is cumbersome, and only some relevant features are noted here. Figure 12 shows the calculated and measured response of a photochromic waveguide grating filter: this component, designed as a normal incidence bandstop filter, demonstrates a bandwidth of about 0·4 nm. The filter characteristic in Fig. 12 shows the presence of significant sidelobes. However, techniques for suppressing the sidelobe levels and tailoring the overall filter characteristic to particular requirements have been studied, and include tapering the strength of the grating along its length (by tailoring the refractive index profile) and 'chirping' the period (i.e. systematically varying the period of the grating). Some results of work performed at A.C.R.C. on photochromic chirped period gratings are described below.

The combination of the deflection characteristic with narrow wavelength bandwidth produced a component that is under development using photochromic waveguides for application in wavelength-division multiplexing and demultiplexing. The bandwidth of a single monomode fibre may be more efficiently utilized by the simultaneous transmission of several modulated carriers, where each carrier has a different wavelength; for this, components to superimpose and separate the individual carriers before and after transmission are required. The scheme using

Fig. 12. Filter response of a photochromic grating with a guided wave incident at normal incidence.



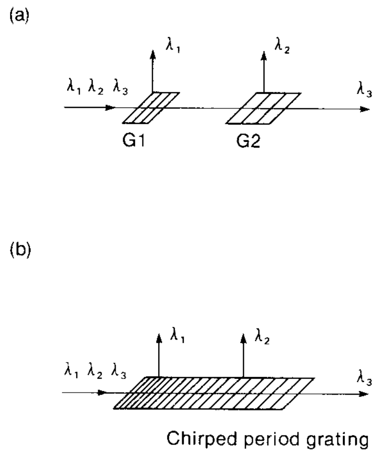
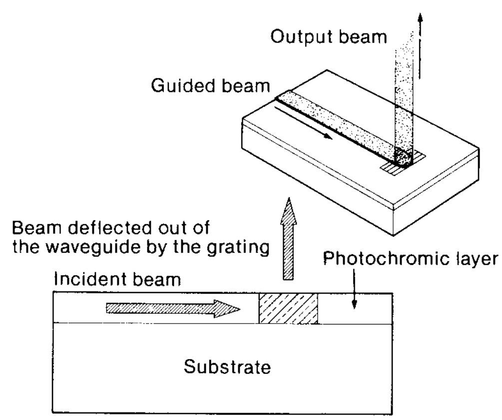


Fig. 13. Wavelength demultiplexing using waveguide gratings, (a) with discrete uniform period gratings, (b) with a single chirped period grating.

Fig. 14. Deflection of guided wave out of a waveguide by a Bragg grating with slanted fringes.

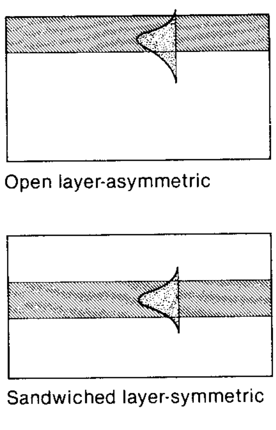


photochromic waveguide gratings is illustrated for the case of a demultiplexer for three wavelengths in Fig. 13(a). The beam input to the waveguide contains wavelengths λ_1, λ_2, λ_3. Gratings G1 and G2 are designed to deflect wavelengths λ_1 and λ_2, respectively, leaving only λ_3 to exit from G2 undeflected. The radiation having individual wavelengths may be subsequently detected. The narrow bandwidth available from the grating deflectors permits the use of closely-spaced carrier wavelengths.

The component illustrated in Fig. 13(a) requires that several individual gratings be produced and accurately aligned. Although this has been successfully carried out for two gratings at A.C.R.C., a second, simpler approach has also been examined, and this is illustrated in Fig. 13(b). A single chirped-period grating is produced by one exposure to the laser interference pattern produced by one plane and one cylindrical converging wavefront; the latter is produced simply by the insertion of a cylindrical lens into one arm of the exposure arrangement of Fig. 11. It may be seen that the Bragg condition is locally satisfied for different wavelengths along the grating; as the period increases, longer wavelengths are deflected. Provided that the chirp rate is sufficiently gradual, efficient deflection of discrete incident wavelengths is achieved with the required spatial separation. As an example of component performance, a chirped photochromic waveguide grating achieved a spatial separation of approximately 3 mm between incident wavelengths of 652 and 674 nm derived, for experimental convenience, from a tunable dye laser. The spatial separation may be altered by changing the chirp rate.

In an isotropic waveguide light polarized within the plane of propagation travels with a slightly higher phase velocity than that polarized in the perpendicular direction. Since the Bragg condition arises from phase-matched reflection, it is not satisfied simultaneously by the two polarizations so that at constant incident angle on a uniform grating, the deflection peaks for the two polarizations are separated by, typically, several angstroms. The light input to the waveguide from an optical fibre contains an arbitrary mixture of the two polarization states, and in a narrowband grating component the deflection efficiency can be seriously degraded by the polarization response. This potential deficiency has been overcome in photochromic gratings produced at A.C.R.C. by introducing a small variation (or chirp) into the period of the grating. A second approach has also been demonstrated whereby a uniform grating can be used in a birefringent photochromic waveguide by choosing the waveguide depth so that both polarizations are propagated with the same velocity, thus equalizing their Bragg responses.

Fig. 15. Field profiles in the depth dimension of optical waveguide structures.



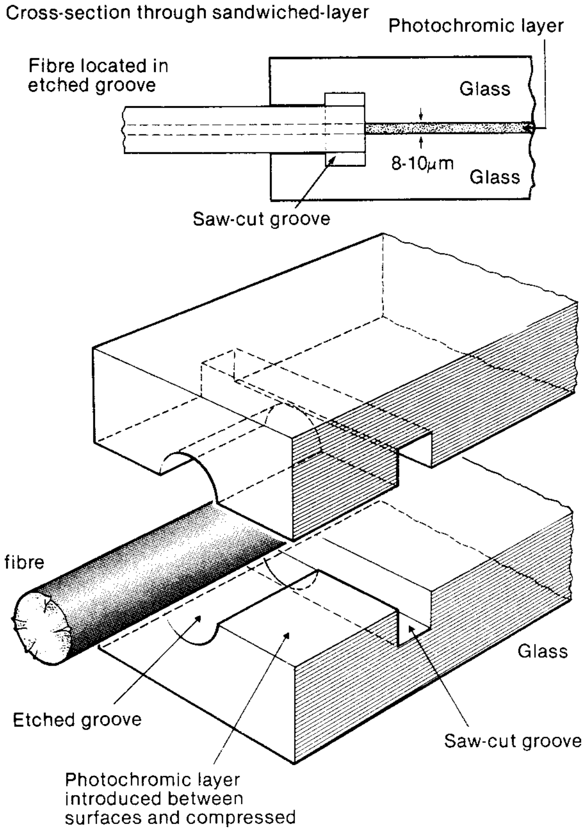


Fig. 16. Fibre-coupling to sandwiched-layer photochromic waveguides.

Finally, a grating may be produced as in Fig. 14, where the fringes are not normal to the waveguide boundaries. In this case, Bragg diffraction produces a beam that propagates out of the waveguide. This component has also been examined in photochromic waveguides with a view to providing a compact and compatible means of coupling light from the waveguide component on to a detector mounted on the upper surface.

5 Fibre-to-Photochromic Waveguide Coupling

All the component principles discussed above can be successfully utilized in a system only if it is possible to transfer light efficiently from monomode fibre to waveguide, and vice versa. The fundamental physical problem is that of matching the field profile of the fibre mode to that of the photochromic waveguide. For a fibre this profile is, of course circular symmetric while that of the photochromic waveguide can never be so. However, a very close approximation can be achieved by matching the electric fields accompanying propagating light in both transverse and depth dimensions, to the cross-section of the fibre modal field. The transverse field is naturally symmetric, as is the depth field of the sandwiched layer structure (Fig. 15). The depth field of the solution-deposited waveguide is asymmetric and, to optimize efficiency, would, in a practical component, be modified to approach symmetry by the addition of a passive overlayer. In the following, discussion is confined to the sandwiched-layer format.

Broadly speaking, it is required to produce a photochromic stripe waveguide with transverse and depth dimensions and refractive index differences similar to the fibre core diameter and core-cladding index difference, respectively. The stripe waveguide must, of course, be capable of supporting only a single mode. The transverse refractive index difference is readily adjustable through the photochromic concentration and u.v. exposure level. For a given stripe index, the substrate index must be adjusted to produce the required difference, and, in the sandwiched-layer structure with glass substrates, this is achieved by means of the ion-exchange technique previously described. In this case, very deep diffusions create essentially uniform cladding layers of the required index adjacent to the photochromic layer. With single-mode sandwiched-layer waveguides produced in this manner the coupling problem largely becomes that of rigidly locating the fibre and stripe waveguide together with their axes accurately aligned.

Figure 16 shows the coupling scheme utilized for photochromic waveguides formed in thermoplastic alkyl resin. The substrates are pregrooved with the arrangement of slots shown in Fig. 16. The saw-cuts are produced first: in assembly they provide flat surfaces against which the fibre ends are contacted. The fibre alignment grooves are produced by chemically etching the glass through a chrome/gold mask prepared by conventional photolithography. For a typical 125 μm diameter fibre, the slot width in the mask is about 10 μm, and the etch process is carefully controlled to produce the semicircular groove profile by undercutting. Grooves in both substrates are etched simultaneously to ensure equal depths. The photochromic layer is deposited by compression of a molten solution as described above. While the layer is still molten, the fibre is introduced into the alignment grooves and manipulated until its prepared flat end contacts the saw-cut groove: in practice, this provides positive location. Alignment of the fibre core with the photochromic layer is accomplished through the accuracy of the etched groove depths. The fibre is cemented in position by excess resin flowing from the layer into the groove.

In components involving several fibres, a mask of the requisite groove pattern is prepared and the photochromic layer deposited with fibres located prior to defining the stripe waveguide pattern by u.v. exposure on the apparatus of Fig. 4. The writing laser spot is viewed through the microscope by observing the fluorescence induced in the photochromic layer, and may be accurately positioned against one input fibre core. The appropriate waveguide pattern interconnecting the fibres is then written. Figure 17 shows a section of one component, showing the written photochromic stripe aligned with the fibre and saw-cut and etched grooves. This technique wherein the waveguide is aligned to the fibre has proved more attractive in terms of ease of fabrication than alternative techniques involving alignment of a fibre to a prewritten waveguide.

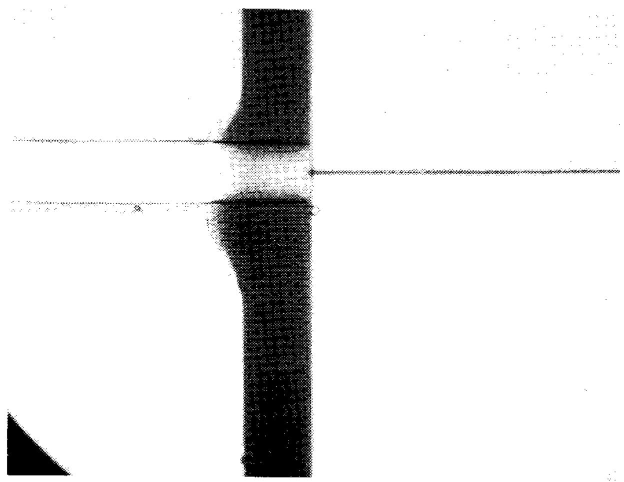


Fig. 17. Photochromic stripe waveguide aligned with a monomode optical fibre in a sandwiched layer structure. The fibre is located in grooves etched in the glass substrate.

6 Conclusions

Principles and techniques for preparing and utilizing photochromic waveguide passive components for fibre-optics have been described, and they are currently being adapted to produce practical components.

The sandwiched-layer provides a robust component format wherein fibre-to-waveguide alignment may be achieved with relative ease and reliability. Particular application areas in monomode systems are seen to include wavelength multiplexers and demultiplexers and routeing components for data distribution networks. The role of photochromic waveguides in active components such as switches remains a possible future development.

7 Acknowledgment

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