(Al: 1 wt.%) and fibre 3 (Al:3 wt.%).

(ii) *Gain degradation*: To examine the effects of γ-rays on the amplification characteristics, the small signal gain for fibre 2 was measured before and after irradiation. The initial gain was 34dB at 1.55μm when pumped at 1.48μm with a launched pump power of 35mW. Gain degradation due to irradiation at each total dose is plotted in Fig. 3. The gain reduction after 25 years at a dose rate of 0.5R/year is estimated to be as small as 0.3dB by extrapolation of results. Additionally, the gain spectra after the irradiation were confirmed to be unchanged at wavelengths around 1.55μm. It is advantageous for multiwavelength applications in the future.

Conclusion: We have presented the results of γ-ray exposure tests for EDFs with different Al content levels, and predicted the long-term loss increase and the gain degradation based on the experiments at low dose rates. It was confirmed that the loss increase and the gain degradation should be negligibly small under realistic conditions.

Acknowledgment: The authors would like to thank T. Ohnishi and Y. Mukumoto of the Univ. of Osaka Prefecture for supporting our measurement.

12 April 1994
Electronics Letters Online No: 19940870

C. Fukuda, Y. Chigusa, T. Kashiwada, M. Onishi and H. Kanamori (*Sumitomo Electric Industries, Ltd., 1, Taya-cho, Sakae-ku, Yokohama 244, Japan*)

S. Okamoto (*Univ. of Osaka Prefecture, 1-2, Gakuen-cho, Sakai, Osaka 593, Japan*)

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π-phase-shifted periodic distributed structures in optical fibres by UV post-processing

J. Canning and M.G. Sceats

Indexing terms: Optical fibres, Germanate glasses, Photolithography

UV post-processing of an inline photolytic grating has allowed the fabrication of a π-phase-shifted distributed phase structure in an optical fibre with a transmission filter of ~100MHz.

Introduction: Although the mechanism is far from understood, the photosensitivity of germanosilicate fibres is used to fabricate reproducible strong fibre Bragg gratings mainly by side-writing with UV light [1]. It is now an established practice to write simple 'uniform' periodic structures greater than 1cm [2] long with reflectivities exceeding 99%. Consequently, attention is shifting to the fabrication of complex grating structures for specific applications.

Point-by-point writing of gratings as demonstrated recently by Malo *et al.* [3] has the significant advantage of allowing arbitrary phase gratings to be written. Tapering of a grating has enabled Byron *et al.* [4] to produce chirped gratings. In this Letter, we demonstrate that UV post-processing, or trimming, of a periodic grating can be used to generate a complex grating, and in particular, the π-shifted distributed phase structure required for a DFB laser.

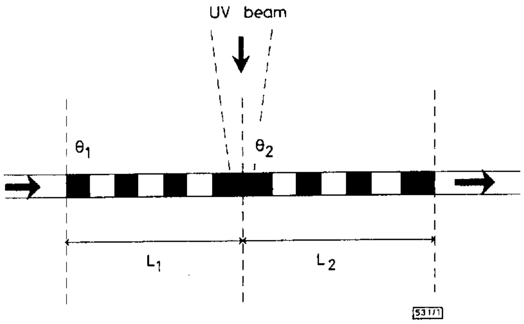

Fig. 1 *Introduction of a phase shift by raising the refractive index at a point along the fibre*

The principle of the phase-shifted grating was originally demonstrated by Alferness *et al.* [5] in periodic structures made from semiconductor materials where a phase shift was introduced by etching a larger spacing at the centre of the device. This forms the basis of singlemode phase-shifted semiconductor DFB lasers [6]. In our scheme we create similar devices in optical fibres by raising the general refractive index at a certain region in the fibre grating through irradiation with UV light, as shown in Fig. 1. Such post-processing produces two gratings out of phase with each other which act as a wavelength selective Fabry-Perot resonator allowing light at the resonance to penetrate the stop-band of the original grating. The resonance wavelength depends on the size of the phase change.

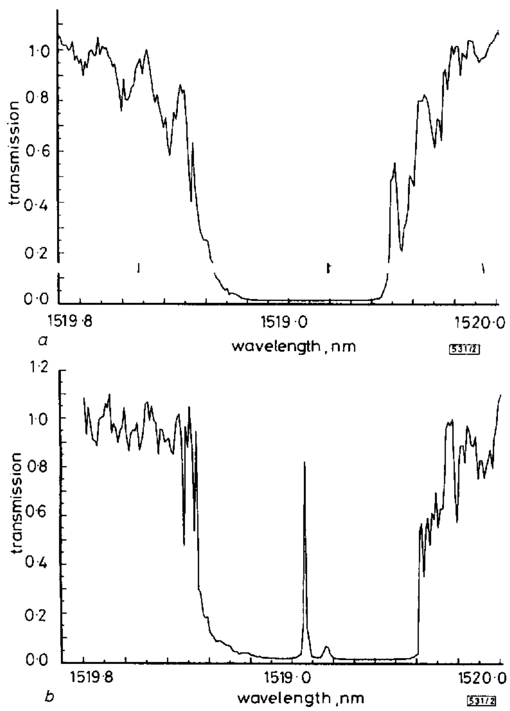

Fig. 2 *Normalised transmission spectra prior to processing, and after processing*

a Prior to processing
b After processing

Experiment: A strong uniform 4cm grating ($R > 99\%$, $\Delta\lambda \simeq 0.15$nm, $\kappa L \sim 3$) was written by translating across a phase mask [2] the 240nm output (repetition rate = 20Hz, pulse fluence $\simeq$1mJ/cm^2, number of shots = 36000) of a frequency doubled Coumarin dye laser pumped at 308nm from an XeCl excimer laser. The transmission spectra (Fig. 2) were obtained by scanning a Hewlett Packard 8168A tunable singlemode laser with a resolution of 0.001nm, centred at ~1520nm, and monitoring the transmitted power. 240nm light was then focused directly onto the centre of the grating over a length of ~1mm. A transmission spike was observed to grow into the reflection bandwidth and after 12000 shots the transmission spectrum of Fig. 2*b* was obtained. Continued processing resulted in no further changes, indicating that the processed region has reached a saturated level of index change. Fig. 3 displays calculated results using the coupled-mode equations for a grating with a π phase shift in the centre and using the matrix treatment of Yamada and Sakuda [7]. In this case the structure is treated as two out of phase gratings, where the grating phase on the left facet (θ_2) of the second grating is related to the phase of the first grating (θ_1) by

$$\theta_2 = \theta_1 + 2\beta_0 L_1 + \Omega$$

where β_0 is the propagation constant, L_1 the length of the first grating and Ω the phase shift induced by the UV processing.

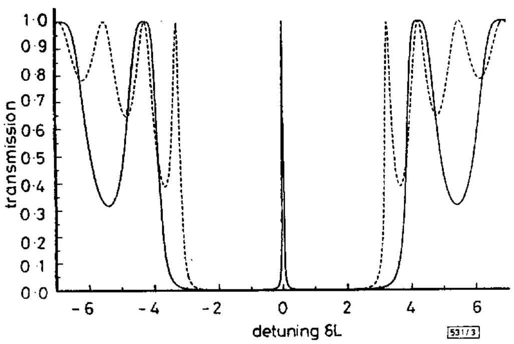

Fig. 3 *Calculated transmission spectrum for a uniform grating ($\kappa L \simeq 3$) without a phase shift, and with a π phase shift*

– – – – without phase shift
——— with π phase shift

Discussion: The experimental results shown in Fig. 2*a* and Fig. 2*b* reveal an overall broadening of the bandwidth of the spectrum as a whole once the phase shift is introduced. Theoretical calculations (Fig. 3) predict this broadening qualitatively together with the expected transmission band. A phase shift close to π has been achieved (Fig. 2*b*). The narrowness of this transmission spike, which is close to the resolution, is influenced by several factors. The predominant factor is the strength of the grating measured as $\kappa L \simeq 3$. This has allowed creation of a high Q resonator with a finesse, i.e. the ratio of the reflection bandwidth to the narrow transmission bandwidth, of >80. In addition, the length of the grating has resulted in very high sensitivity to external perturbations such as temperature and strain where potential applications in sensor devices involving detuning of the resonator to detect small changes in the measurand can be envisaged.

Conclusions: We have presented results showing that simple localised post-processing of a Bragg grating by UV light can introduce phase shifts which will influence the transmission and the reflection spectra of these gratings. This technique is clearly versatile, because it can also be applied during grating writing, and has the potential of being extended to modify spectral properties in even more complex ways. Trimming of the structure can be observed *in situ*. The most obvious applications include production of very narrowband transmission and reflection filters. Moreover, multiple phase shifts can be introduced to produce other devices such as comb filters. However, the sensitivity to environmental perturbations of such long grating structures, which will influence the finesse of the device, may make them ideal for sensor applications. They can also be used to obtain singlemode operation of DFB fibre lasers. In summary we have demonstrated the first steps towards a simple means of photolithographically post-processing a grating so that its properties are tailored for desired applications.

Acknowledgments: The authors would like to thank the Gratings group at the OFTC for their support in this work. This work was carried out under the auspices of the Australian Photonics Cooperative Research Centre of which the OFTC is a member.

14 June 1994
Electronics Letters Online No: 19940920

J. Canning and M. G. Sceats (*Optical Fibre Technology Centre, University of Sydney, Sydney, NSW, Australia*)

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Vacuum poling: an improved technique for effective thermal poling of silica glass and germanosilicate optical fibres

P.G. Kazansky, L. Dong and P.St.J. Russell

Indexing terms: Optical fibres, Optical harmonic generation

The use of thermal poling in a vacuum to eliminate the spreading out of the poled regions beyond the boundaries of the positive electrode is proposed and experimentally demonstrated. A substantial improvement in reproducibility and quality of the induced second-order susceptibility is achieved.

Myers *et al.* [1] showed that a second-order nonlinearity of the order of 1pm/V can be induced in fused silica by thermal poling, which has opened up the prospect of linear electro-optic modulators and frequency converters monolithically integrated into optical fibres or planar glass waveguides. During thermal poling in fused silica, a 1mm thick sample is heated to ~250 – 300°C at an applied voltage 3 – 5kV. After cooling and removal of the applied field, the second-order nonlinearity is observed only near the anodic surface. This can be explained by the appearance of a high electrostatic field (of order 10^7V/cm) in a thin depletion region near the anodic surface [1]. We have suggested that this frozen-in electrostatic field arises between two layers of space charge near the anodic surface: A negatively charged layer depleted with cations, and a positively charged layer created by ionisation in the high field between the depleted layer and the anode [2]. However some aspects of this phenomenon, such as substantial lateral spreading of the second-order nonlinearity beyond the boundaries of the positive electrode, are not fully understood. We have suggested that this spreading may be caused by the surface conductiv-