The short wavelength loss seen in the transmission spectrum at wavelengths < 1555nm is due to radiation mode coupling in the fibre used for the experiment, and can be reduced by the use of cladding photosensitive sensitive optical fibre [5].

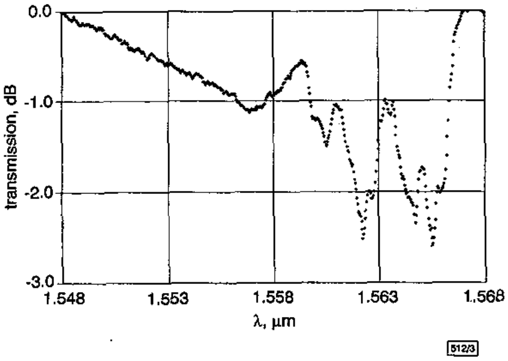

Fig. 3 *Transmission spectrum of 15cm long Bragg grating written with circular phase mask*

It is clear that with improvements to the system, it should be possible to fabricate quality ultra-long, long and short period gratings. An interesting fact to note is the ease with which the short-period grating is inscribed using the rotating phase mask with no interferometric control other than that determined by the location of the fibre, and that the principle of fabricating long, continuous Bragg gratings using a circular phase mask has been demonstrated.

Conclusions: To our knowledge, we have demonstrated a novel method for fabricating infinitely long gratings by the use of circular amplitude and phase masks for the first time. There are several variations which may be easily implemented. These include the combination of different period long period amplitude masks to generate moiré patterns [2] in a continuous fashion. This also applies to short-period gratings, and the combination of amplitude and phase masks is a convenient method of writing long, moiré and sampled gratings, producing superstructures in the transmission spectra. This technique should be suitable for a large number of applications; for example, in the fabrication of precise, long and short period gratings and Fabry Perot interferometers and chirped gratings.

© IEE 1999 *28 July 1999*
Electronics Letters Online No: 19991266
DOI: 10.1049/el:19991266

R. Kashyap, A. Swanton and R.P. Smith (*BT Laboaratories, Martlesham Heath, Ipswich IP5 3RE, United Kingdom*)

E-mail: raman.kashyap@bt.com

References

1 MARTIN, J., LAUZON, J., THIBAULT, S., and OUELLETTE, F.: 'Novel writing technique of long highly reflective in fiber gratings and investigation of the linearly chirped component'. Proc. Conf. Optical Fiber Communications, OFC '94, 1994, Vol. 138, Post Deadline paper PD29-1

2 KASHYAP, R.: 'Fiber Bragg gratings' (Academic Press, 1999), Chap. 3

3 KASHYAP, R.: 'Infinite length gratings'. BT Patent No. EP 96300295.1

4 ALBERT, J., THERIAULT, S., BILODEAU, F., JOHNSON, D.C., HILL, K.O., SIXT, P., and ROOKS, M.J.: 'Minimisation of phase errors in long fiber Bragg grating phase masks made using electron beam lithography', *IEEE. Photonics Technol. Lett.*, 1996, **8**, (10), pp. 1334–1336

5 DELAVAQUE, E., BOJ, S., BAYON, J.-F., POIGNANT, H., LE MELLOT, J., MONERIE, M., NIAY, P., and BERNAGE, P.: 'Optical fibre design for strong grating photo imprinted with radiation mode suppression'. Proc. OFC'95, 1995, Post-Deadline Paper PD5

Loss-tunable long period fibre grating made from etched corrugation structure

C.Y. Lin and L.A. Wang

A new long period fibre grating (LPFG) is demonstrated, for which the transmission loss at the resonance peak can be tuned from 1.2 to 29dB after fabrication. For such a large tuning range, the shift of the peak loss wavelength is < 2.2nm. The tunability is obtained by adjusting the amount of stress applied to the LPFG, composed of an etched corrugation structure. No light exposure is required.

Introduction: Recently LPFGs have attracted much attention for use in many applications such as band-rejection, gain shaping and sensing, etc. Different techniques have been developed for the fabrication of LPFGs. Most of these techniques require photosensitive fibres. Other techniques that do not require photosensitive fibres have been reported, including the use of focused CO_2 laser pulses [1], electric arc [2] and residual stress relaxation [3, 4]. However, the periodic index variation in these reported LPFGs cannot be tuned to give different coupling strengths from weak to strong, i.e. loss tunability, after fabrication. We propose a novel loss-tunable LPFG, the periodic index variation of which can still be tuned over a large range to allow loss tunability from weak (1.2dB) to strong (29dB) after fabrication. Unlike conventional LPFGs where the peak loss wavelength often shifts considerably during the growth process [5], the proposed LPFG remains relatively stable during loss tuning. Such a loss-tunable LPFG can be fabricated in any type of fibre, because no photosensitivity is required for the grating formation.

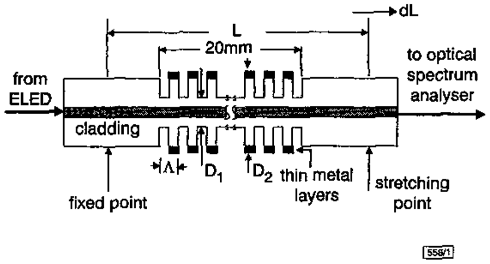

Fig. 1 *Schematic diagram of LPFG defined by corrugated structure and measurement setup for characterising loss tunability*

Principle: The corrugated structure shown schematically in Fig. 1 is built directly into the fibre cladding by chemical etching. When the etched section is placed straight and free from tensile strain, an effective waveguide index modulation results due to the corrugated structure. Such modulation is very small unless the dimension *D* is etched close to the fibre core. The coupling efficiency between the core and cladding modes is therefore very small, i.e. a weak LPFG with small resonant loss. However, when a stress is applied, a much stronger index variation is induced in the corrugated structure. This is because the strain is inversely proportional to the square of the diameter [6], and the induced index Δn resulting from photoelastic effect is proportional to the applied stress multiplied by the difference between inverse squares of the diameters $(1/D_1^2 - 1/D_2^2)$. The index variation increases with stress and results in an LPFG with increasing resonant loss, on which the tunability is based. Note that unlike most reported LPFGs where the index variations occur in the core only, the index variations of the proposed LPFG occur in both the core and cladding over the entire corrugated structure. Such an effect would therefore create a stronger coupling, resulting in a larger loss in the transmission spectrum.

It has been shown that for a conventional LPFG, as an average grating index variation δn_{core} increases, the wavelength λ_{max} at which resonant coupling occurs can be written as [5]

$$\lambda_{max} \simeq \lambda_{res}\left(1+\frac{\delta n_{core}\frac{d\lambda_{res}}{d\Lambda}}{(n_{core}-n_{clad})^2}\right) \qquad (1)$$

where λ_{res} is the initial resonant wavelength, n_{core} and n_{clad} are effective indices of the fundamental core and cladding modes, respectively, and Λ is the grating period. Here it is assumed that the index change only occurs in the core, and thus the change in the cladding index is close to zero and can be neglected. For the proposed LPFG, the index change of the cladding, δn_{clad} is close to that of the core, δn_{core}, and cannot be neglected. Eqn. 1 should therefore be modified to:

$$\lambda_{max} \simeq \lambda_{res}\left(1+\frac{(\delta n_{core}-\delta n_{clad})\frac{d\lambda_{res}}{d\Lambda}}{(n_{core}-n_{clad})^2}\right) \qquad (2)$$

Since the difference ($\delta n_{core} - \delta n_{clad}$) in eqn. 2 is much less than δn_{core} in eqn. 1, it is expected that the shift of the resonant wavelength will be much smaller than that of a conventional LPFG.

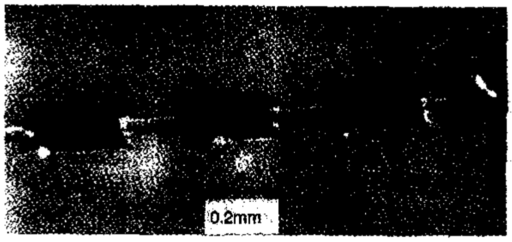

Fig. 2 *Prototype LPFG*

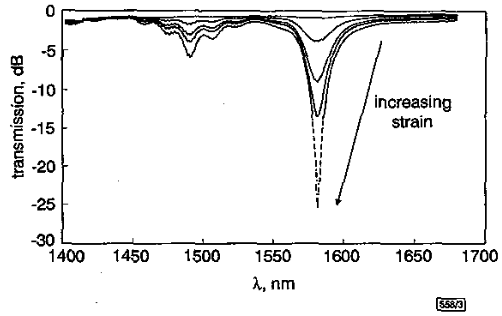

Fig. 3 *Evolution of transmission spectra when strain is applied to LPFG*

Experimental results: The corrugated structure was built in the following way. A standard dispersion-shifted fibre with an original cladding diameter (D_2) of 125μm was used. Thin layers of metal with a total thickness of ~120nm were coated onto the fibre with a special setup to form a segmented ring pattern for etching protection when immersed in hydrofluoric acid solution. The uncoated sections were etched to a diameter (D_1) of ~ 42μm, as shown in Fig. 2. The corrugated structure has a period of 400 μm over a total length of 20mm. The experimental setup for characterising the loss tunability is also shown in Fig. 1 in which an external stress was applied to induce a strain dL/L. The transmission spectra of the LPFG with different stresses are shown in Fig. 3. It can be seen that the transmission loss at the resonance peak increases with stress because the index difference in the region of the diameters D_1 and D_2 becomes larger. The measured wavelength shift is < 2.2nm during the overall loss tuning. The relationship between the applied strain and the loss magnitude measured at the peak wavelength is shown in Fig. 4. The loss is < 1.2dB when no stress is applied, and is > 29dB when the strain dL/L is ~0.58mstrain. Note that such loss tuning is very sensitive when compared to conventional LPFGs [7]. This result also shows that when further strain is applied, the transmission loss decreases due to the reverse coupling from the cladding mode to the core mode, which is similar to the over-exposure case commonly observed in the fabrication of photo-induced LPFGs.

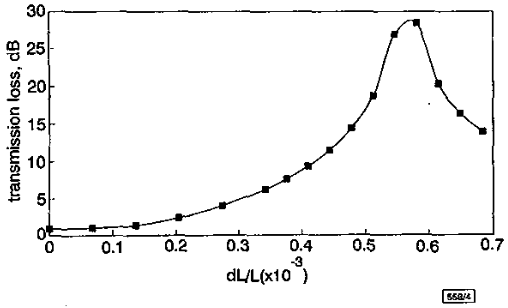

Fig. 4 *Transmission loss against strain measured at peak loss wavelength*

Conclusion: We have demonstrated, for the first time to our knowledge, a new technique to fabricate a loss-tunable LPFG by varying the stress applied to a corrugated structure where the LPFG is defined. The strain variation, resulting from the difference in the etched and unetched diameters over the corrugated structure, induces an index variation, and thus provides the mechanism of tunability. Measured results show that the loss tunability can be obtained from 1.2 to 29dB for the LPFG with very small applied strains. Additionally, the less than 2.2nm shift in the peak loss wavelength shows good stability during the tuning process. Such a loss-tunable LPFG may find uses in optical fibre communication and fibre sensing applications.

27 August 1999
Electronics Letters Online No: 19991143
DOI: 10.1049/el:19991143

C.Y. Lin and L.A. Wang (*Department of Electrical Engineering and Institute of Electro-Optical Engineering, National Taiwan University, Taipei, Taiwan, Republic of China*)

E-mail: lon@ccms.ntu.edu.tw

L.A. Wang: Corresponding author

References

1 DAVIS, D.D., GAYLORD, T.K., GLYTSIS, E.N., KOSINSKI, S.G., METTLER, S.C., and VENGSARKAR, A.M.: 'Long-period fibre grating fabrication with focused CO_2 laser pluses', *Electron. Lett.*, 1998, **34**, pp. 302–303
2 KOSINSKI, S.G., and VENGSARKAR, A.M.: 'Splicer-based long-period fiber gratings'. OFC'98, 1998, pp. 278–279
3 AKIYAMA, M., NISHIDE, K., SHIMA, K., WADA, A., and YAMAUCHI, R.: 'A novel long-period fiber grating using periodically released residual stress of pure-silica core fiber'. OFC'98, 1998, pp. 276-277
4 ENOMOTO, T., SHIGEHARA, M., ISHIKAWA, S., DANZUKA, T., and KANAMORI, H.: 'Long-period fiber grating in a pure-silica-core fiber written by residual stress relaxation'. OFC'98, 1998, pp. 277–278
5 MacDOUGALL, T.W., PILEVAR, S., HAGGANS, C.W., and JACKSON, M.A.: 'Generalized expression for the growth of long period gratings', *J. Lightwave Technol.*, 1998, **10**, pp. 1449–1451
6 SONG, M., LEE, B., LEE, S.B., and CHOI, S.S.: 'Interferometric temperature-insensitive strain measurement with different-diameter fiber Bragg gratings', *Opt. Lett.*, 1997, **22**, pp. 790–792
7 BHATIA, V., and VENGSARKAR, A.M.: 'Optical fiber long-period grating sensors', *Opt. Lett.*, 1996, **21**, pp. 692–694

Waveguiding properties of holey fibres and effective-V model

R. Ghosh, A. Kumar and J.-P. Meunier

The authors examine the waveguiding properties of holey optical fibres made with circular silica tubes. The effective index of the fundamental mode and the first higher-order mode cutoff wavelength have been obtained for different fibres. The effective-*V* model is found to be unsuitable in describing the guiding properties of such fibres.

Introduction: Recently, a considerable amount of work has been reported on holey optical fibres (HFs) [1 – 7], due to their unusual waveguiding properties. These fibres have a cladding region comprised of air holes running along the full length of the fibre. Two different types of HF are reported in the literature, one made with circular tubes [1] (HFCT), while the other is made with hexagonal rods with central air holes, popularly known as PCF. These fibres guide light due to a central defect in an otherwise periodic