probably induced as a result of the loss of signal-to-noise ratio from the NDFWM process. Pattern length dependent effects due to gain saturation could also be present which would act detrimentally on the conversion process. As this is not an optimised device for NDFWM, there is considerable scope for improvement in future designs by lengthening the SOA section and optimising the active region as reported by Kelly *et al.* [5].

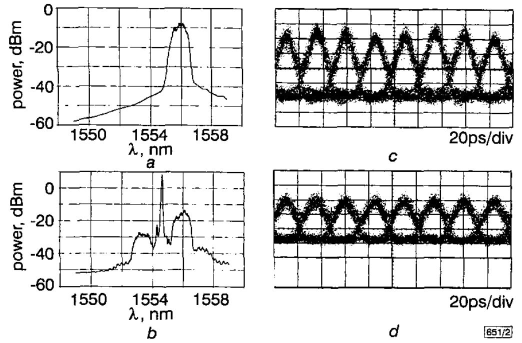

Fig. 2 *Input and output spectra and eye diagrams*

a Input 40Gbit/s spectrum
b Output spectrum from SOA section of wavelength converter displaying generated phase conjugate wavelength converted signal at 1553.2nm
c Input 40Gbit/s eye diagram at 1556nm
d Wavelength converted 40Gbit/s eye diagram at 1553.2nm

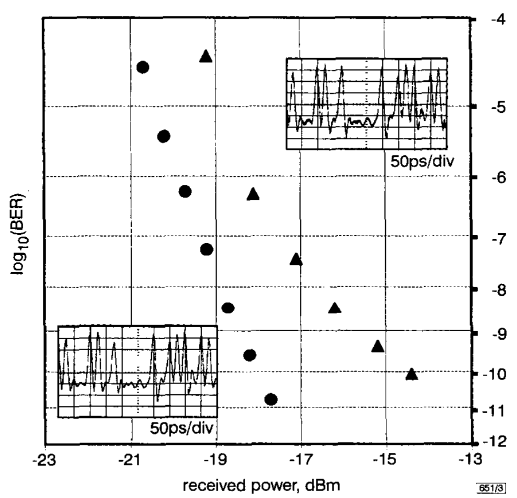

Fig. 3 *Bit error rate for both back-to-back (10-40-10Gbit/s) 2^7–1 signal at 1556nm and wavelength converted signal at 1553nm*

Inset: 40Gbit/s input (lower left) and converted (upper right) patterns included for comparison
● back-to-back 40Gbit/s signal at 1556nm
▲ wavelength converted to 40Gbit/s signal at 1553.2nm

Conclusions: A novel device has been demonstrated to provide a compact and stable platform for performing all-optical wavelength conversion using non-degenerate four wave mixing. The device consists of an integrated DFB pump laser and an SOA. Successful conversion of a 40Gbit/s signal from 1556 to 1553.2nm has been demonstrated with a BER sensitivity penalty of 2.5dB. The sub-picosecond carrier dynamics inherent to the NDFWM process in SOAs lead us to expect that devices similar to this should be able to convert at data rates up to 100Gbit/s [3]. The device could also be used as a mid-span spectral inversion component to provide dispersion compensation for high bit rate links [6].

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Optical coupling between singlemode fibres by utilising long-period fibre gratings

W.T. Chen and L.A. Wang

A new coupling scheme between singlemode fibres utilising a lensed fibre integrated with a long-period fibre grating (LPFG) is experimentally demonstrated. The measured results show that for a lens with an appropriate radius, the use of an LPFG would lead to a higher coupling efficiency over a range of long working distances than that obtained without using the LPFG.

Introduction: Recently, long-period fibre gratings (LPFGs) have been demonstrated for various applications including band-rejection filters, gain equalisers, mode converters, rocking filters and sensors [1 – 3]. Here, we demonstrate another application by utilising an LPFG for optical coupling. Traditionally, a high coupling efficiency between singlemode fibres can be achieved by using a mechanical connector such as a PC or SC, which results in very restricted working distances and tolerances [4]. Techniques employing discrete or integrated optical components such as GRIN rods, spherical and aspherical lenses can be used to increase the working distance and/or tolerances. We propose an alternative by integrating an LPFG with a hemispherical lensed fibre so that the coupling efficiency can be increased markedly over a range of long working distances.

Experiment setup and results: The proposed new coupling scheme is shown schematically in Fig. 1. Two singlemode fibres, SMF1 and SMF2, of dispersion-shifted type are used in the experiment. The beam emitted from SMF1 has a mode field diameter of 8μm measured at the full width of the $1/e^2$ intensity distribution. After propagating a working distance Z_s, the Gaussian beam is transformed by a hemispherical lensed fibre having a radius of R_1. Depending on the lens radius, some proportion of the transformed beam will excite the cladding modes, which are then coupled back into the core mode in region III with the aid of an LPFG. It is noted that only the cladding modes that are phase matched with the grating can be converted efficiently into the core mode at a specific wavelength. The coupling efficiency can be expressed as P_{SMF2}/P_{SMF1}, where P_{SMF1} and P_{SMF2} are the emitted and received optical power measured from the output ports of SMF1 and SMF2, respectively.

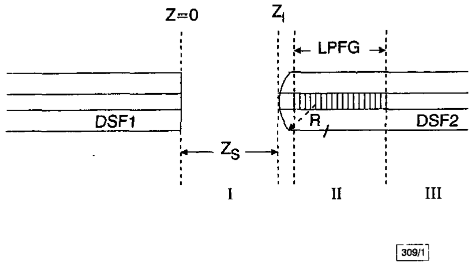

Fig. 1 *Schematic diagram of new coupling scheme*

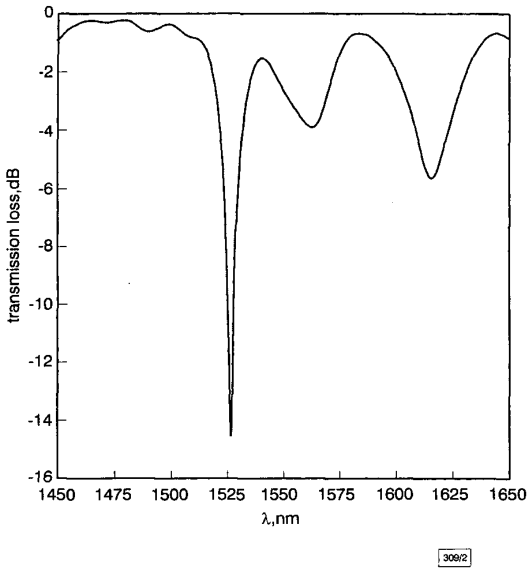

Fig. 2 *Transmission spectrum of LPFG*

A wavelength-tunable laser diode is used as a light source and its output wavelength is chosen to match the maximum transmission loss of an LPFG. The laser has a linewidth of 0.2nm measured at FWHM, and its output is connected to SMF1. An LPFG is imprinted in SMF2 by using 248nm UV-exposure through an amplitude mask of period 450μm. The SMF2 has been pre-hydrogenated for 15 days at a pressure of 1500psi. The UV-exposed area is ~20mm in length. The LPFG thus imprinted is subject to annealing for the stabilisation of the spectral characteristics. The transmission spectrum of the annealed LPFG is shown in Fig. 2. SMF2 is then cleaved near the endface of the UV exposed area to form a hemispherical lens by utilising electric arc discharge. The radius of curvature is controllable to a precision of 10μm. The two SMFs are placed on the holders of an automatic alignment setup to determine the maximum coupling power in space at a given working distance.

Fig. 3 depicts the variation of coupling efficiency with working distance for various radii. The solid and dashed curves correspond to the fibre with and without the LPFG, respectively. For a lensed fibre without an LPFG, the coupling efficiency reaches its maximum at a very short working distance, and then decreases monotonically after that distance has been reached. The behaviour is very similar to that of butt coupling owing to the relatively large radii employed. Conversely, for a lensed fibre with an LPFG, the working distance can be increased markedly with a tradeoff in efficiency. For a lens radius of 100 μm, the maximum coupling efficiency is ~58% at a working distance of 213μm, and the corresponding longitudinal tolerance is ~ ± 22μm at 1dB loss. For other radii of 135 and 180 μm, the optimal working distances are 300 and 375μm with corresponding coupling efficiencies of 51 and 43%, respectively. Their longitudinal tolerances at 1dB loss are ~ ±30 and ±44μm, respectively. Note that over such a long range of working distances, only lensed fibre which has an LPFG will have a high coupling efficiency. For example, over a working distance of ~ 200–225μm the coupling efficiency for the fibre with 100μm-radius lens is > 50%, and is ~ 2.7–3.5 times greater than that without the assistance of an LPFG. When the receiving fibre is cleaved only, i.e. with the radius of infinity, the coupling efficiency gradually increases with the separation, and becomes nearly saturated to 8% at a separation of 425μm.

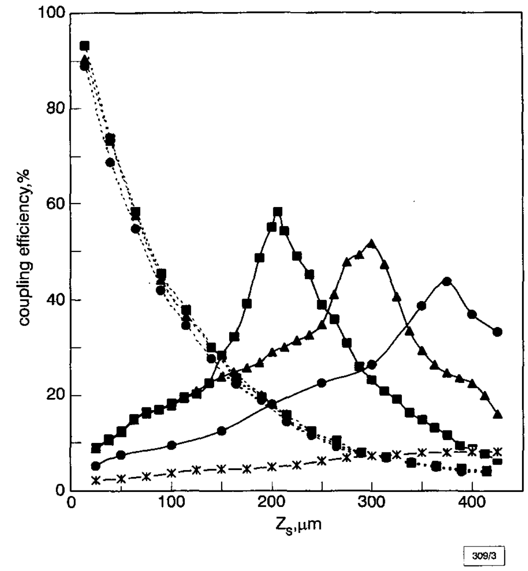

Fig. 3 *Coupling efficiency against working distance for lensed fibres with various radii*

- - - - coupling without LPFG
■ R_l = 100μm
▲ R_l = 135μm
● R_l = 180μm
✳ R_l = ∞

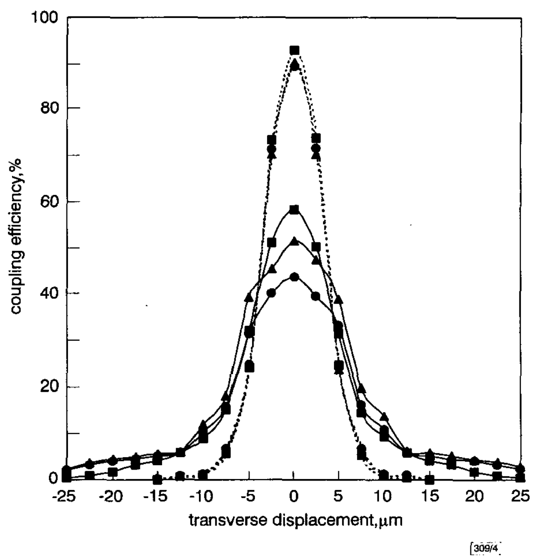

Fig. 4 *Coupling efficiency against transverse displacement for lensed fibres with various radii*

- - - - coupling without LPFG
■ R_l = 100μm
▲ R_l = 135μm
● R_l = 180μm

Fig. 4 shows the variation of coupling efficiency with transverse displacement for lensed fibres with various radii. The measured transverse tolerances at 1dB loss of their peak efficiencies are estimated to be ±3.2, ±4.5 and ±4.5μm for the fibres with radii of 100, 135 and 180μm, respectively. All of the tolerances are greater than those obtained without the aid of the LPFG. It is noted that such tolerances are also greater than obtained using butt-coupling, which typically has a transverse tolerance of ~ ±1.8μm at 1dB loss [5]. The coupling efficiency depends on several parameters including the magnitude of the transmission loss of the LPFG, the wavelength difference between the laser and LPFG, and the separation between the lens and the LPFG and lens radius, which is currently under study for optimisation. To the first-order calculation, it is found that the separation between the lens and the LPFG plays an important role for obtaining optimal efficiency. An experimental technique for identifying the exact location of the LPFG is therefore required.

Conclusion: We have demonstrated a new scheme for optically coupling singlemode fibres by utilising a lensed fibre and an LPFG. This coupling scheme has several unique features. First, over a range of long working distances, > 50% coupling efficiency with large transverse tolerance can be obtained, which is helpful in the packaging process as well as in reducing optical back reflection. Secondly, the use of a lens with a relatively large radius may relax the stringent requirements on the fabrication process as compared to that for conventional lensed fibres, which generally have small radii. Other applications for this new coupling scheme are also expected, for example, in the coupling of output light from a laser diode to a singlemode fibre.

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Suppression of cladding mode coupling in Bragg grating using Ge_2O-B_2O_3 codoped photosensitive cladding optical fibre

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A new type of photosensitive optical fibre codoped with Ge_2O-B_2O_3 in both the core and cladding has been fabricated for applications in Bragg gratings. Coupling of the fundamental core mode into the cladding modes was suppressed with a narrow 3dB bandwidth in the Bragg grating. An increase in photosensitivity was also achieved by using high reflectivity Bragg gratings imprinted without the need for any hydrogen treatment.

Photoinduced fibre Bragg gratings (FBGs) have received consistent attention in areas of application such as narrowband reflection filters, add-drop filters, dispersion compensators and sensors [1]. In a high reflectivity grating, however, a wide loss band due to cladding mode coupling restricts the use of FBGs particularly in dense wavelength division multiplexing (WDM) systems. Coupling from the forward-propagating fundamental core mode into discrete backward-propagating cladding modes has been attributed to non-uniform effective index modulation over the fibre cross-section and the inherent asymmetry of the blazed FBGs resulting in significant losses below the Bragg wavelength [2].

Various optical fibre designs have been proposed to reduce the cladding mode coupling loss [3 – 5]. In particular, in terms of uniform index modulation, it has been proposed that the photosensitive area be extended into the inner cladding region by codoping with GeO_2 and F [3]. This approach is of interest because two profiles, the refractive index profile and photosensitivity profile, can be designed separately such that the guiding properties of the fundamental core modes are determined by the refractive index profile, while the overlap integral between the core mode and cladding modes is determined by the photosensitivity profile.

Among various silica based glass hosts, silica codoped with B_2O_3 with GeO_2 has been reported to have enhanced photosensitivity by an order of magnitude [6]. However only a few applications of this glass composition in FGBs have been reported.

In the work described in this Letter, uniform index modulation over the inner cladding region has been achieved by utilising highly photosensitive GeO_2-B_2O_3 codoped silica glass, leading to a new type of photosensitive optical fibre for FBGs in WDM device applications. The fibre was designed to suppress cladding mode coupling as well as to enhance the photosensitivity by adjustment of the GeO_2 and B_2O_3 concentration both in the core and cladding regions, which is reported for the first time, to the best of our knowledge.

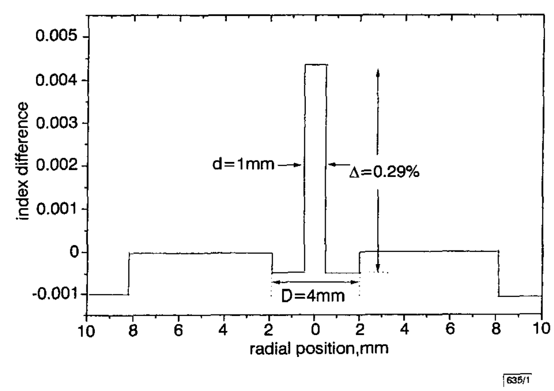

Fig. 1 *Preform index profile*

d: core diameter
D: inner cladding diameter

The preform was made by a modified chemical vapour deposition process using BCl_3 and $GeCl_4$ as precursors of their oxides. The structure of the preform is shown in Fig. 1. The core was doped with 7mol% GeO_2 and 20.15mol% B_2O_3. The inner cladding was doped with 1.25 mol % GeO_2 and 5.8mol% B_2O_3. Note that the inner cladding diameter to core diameter ratio was kept to 4 to increase the photosensitive area. The total index difference Δ was set to 0.294%, similar to that of conventional singlemode fibre, to reduce the splicing loss. The optical fibre was drawn from the preform with LP_{11} mode cutoff at 900nm.

Without any hydrogen treatment, a Bragg grating was formed in the fibre by irradiating it with 248nm KrF laser at 165mJ^{-2} per pulse, at a pulse repetition rate of 20Hz over a phase mask. The transmission spectrum of the imprinted Bragg grating is shown in Fig. 2. To utilise the Bragg reflection filter in dense WDM systems, both narrow bandwidth and high reflectivity are required as well as the suppression of cladding mode coupling losses. A peak reflectivity of 99.23% and 3dB bandwidth of 0.28nm were achieved. The maximum cladding mode coupling loss was measured to be < 0.96dB. In conventional hydrogen treated FBG filters, post-annealing is necessary to stabilise the spectral response. The intrinsic high photosensitivity of the fibre in this study obviated the need for not only the hydrogen loading process before imprinting of the FBGs but also the post-annealing process.