believe that this performance degradation is due to soliton interactions enhancing the Gordon Haus jitter [8]. This was verified in principle by eliminating alternate pulses (to give 20Gbit/s), where significantly enhanced transmission performance was established. Below the optimum transmission wavelength, polarisation mode dispersion was expected to have a major effect on pulse stability (theoretically within the dotted region of Fig. 3) and the error free distance rapidly degraded to 1100km, even for 20Gbit/s signals; however, similar performance below the zero dispersion wavelength was obtained suggesting that, at these distances, soliton effects are no longer of importance. Note that even though the soliton period is less than six amplifier spacings within the hashed region of Fig. 3, stable soliton transmission is still achieved. Taking these degradations into account, we find that for soliton transmission, error free distances over 2000km are possible for soliton centre wavelengths over a 0.7nm range, while psuedolinear transmission over 1000km is possible with an allowed variation in centre wavelength in excess of 2.3nm.

Conclusions: We have shown that linear transmission of 40Gbit/s data sequences over 1000km is possible over a range of wavelengths in excess of 2.3nm, confirming previously reported results. However, the system performance is significantly enhanced to over 2000km for a narrow range of wavelengths (0.7nm) where soliton transmission is possible. The performance of the soliton system appears to be restricted primarily by soliton interactions, and consequently we may expect significantly enhanced performance towards the theoretical limit by employing alternating amplitude or polarisation. This excellent performance is, of course, available without recourse to system specific soliton control techniques.

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A.D. Ellis, T. Widdowson and X. Shan (*BT Networks and Systems, BT Laboratories, Martlesham Heath, Ipswich IP5 7RE, United Kingdom*)

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All-fibre interrogation technique for fibre Bragg sensors using a biconical fibre filter

A.B. Lobo Ribeiro, L.A. Ferreira, M. Tsvetkov and J.L. Santos

Indexing terms: Fibre optic sensors, Strain sensors, Gratings in fibres

A passive self-referencing all-fibre technique for Bragg wavelength shift detection using a biconical fibre filter is described. This filter, basically a tapered depressed-cladding fibre, exhibits a periodic spectral power dependence which permits direct tracking of wavelength shifts in a 20nm unambiguous range. Dynamic strain resolution of 1.5μstrain/√Hz has been achieved.

A considerable research effort has been made during the past few years to develop simple and inexpensive techniques to detect wavelength shifts in fibre Bragg gratings [1], especially in systems using these devices for sensing strain and temperature. High resolution techniques, based on the use of interferometric detection [2], fibre Fabry–Perot filters [3] and acoustic-optic tunable filters [4], were demonstrated. However, these solutions are considerably complex and expensive, and in most engineering applications high resolution may not be required. In this context, a more practical and low cost demodulation technique based on the wavelength dependence of a bulk optical filter has been demonstrated [5]. In this scheme, the backreflected light from the Bragg grating sensor is split into two beams, one of them being spectrally filtered so that its transmitted intensity is determined by its wavelength, while the other beam is used for power referentiation. Provided the filter cutoff is close to the Bragg wavelength, the resulting ratio of the two intensities is proportional to the wavelength of the backreflected light, and independent of the optical power fluctuations along the system. Here, we demonstrate the use of this wavelength discrimination principle using a biconical fibre filter (BFF) [6], a solution that avoids the problems of unwanted reflections and power loss usually present in bulk optical systems. This filter is basically a section of singlemode depressed-cladding fibre, which consists of a contracting tapered region of decreasing fibre diameter followed by an expanding taper of increasing fibre diameter. The wavelength response of the filter is oscillatory with a large modulation depth, propagating only certain wavelengths through the fibre while heavily attenuating others. Other recent approaches for fibre Bragg sensing demodulation use wavelength division fibre couplers as the wavelength discriminator, simplifying the intensity referentiation [7, 8]. However, WDMs are in general expensive components and require fabrication processes more complex than the one needed to produce the biconical fibre filter (BFF).

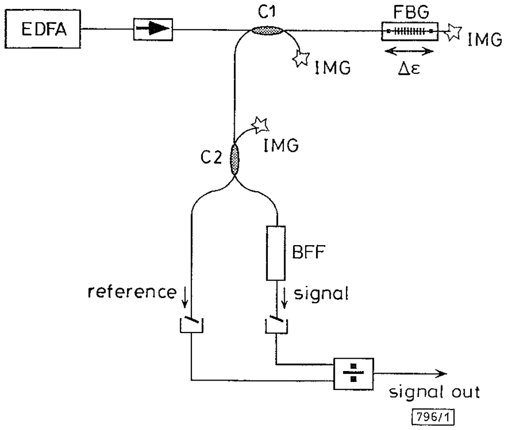

Fig. 1 *Schematic diagram of demodulation scheme*
IMG: index matching gel; Δε: applied strain

Fig. 1 shows the demodulation scheme. An erbium-doped fibre superfluorescent source (EDFA with a dopant level of 2000ppm) was the broadband light source used to illuminate the FBG sensing element via one port of a typical 3dB fibre optic coupler (C1).

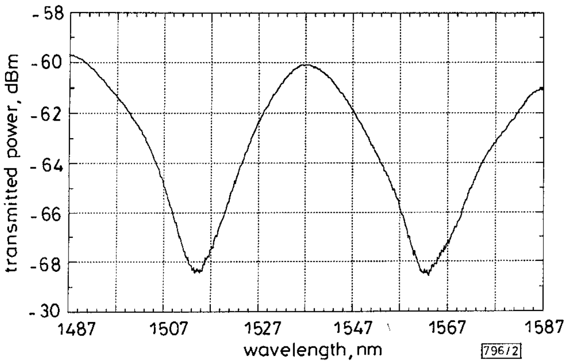

Fig. 2 *Biconical fibre filter transfer function (a white light source was used to illuminate the device)*

A fibre isolator was used to avoid lasing of the source. The FBG demonstrated a Bragg wavelength of 1524nm at room temperature and unstrained, with a reflectivity of ~95% and bandwidth of ~0.2nm. The returned wavelength component from the FBG was split again by a second 3dB coupler (C2) into two paths: in one path the intensity was directly measured while in the other it passed through a biconical fibre filter (BFF) before reaching a detector. The BFF, exhibiting the transfer function shown in Fig. 2, was designed with an oscillation period of ~45nm and an extinction ratio of ~8dB. Over the range 1520 – 1530nm, the filter shows a near linear response of ~0.5dB/nm. To measure the wavelength shift of the FBG sensor, the ratio of the two detected intensities was implemented using an electronic analogue divider. In this way, compensation is performed for time-varying intensity fluctuations and spectral intensity variations of the broadband source, and also for any coupling loss and microbend fluctuations up to coupler C2. This coupler must have a coupling ratio that has a negligible wavelength dependence compared with the transfer function of the BFF. The FBG sensor was bonded to a piezoelectric transducer and subjected to axial strain by applying high voltage to the transducer. Fig. 3 shows the sensor output response for induced axial strains up to 700μstrain. Here, linearity can be observed throughout the measured region and the obtained data indicates a static strain resolution of ~±3.5μstrain. To measure the dynamic strain resolution of the sensing system a 7.8μstrain amplitude signal at ~8Hz was applied to the FBG. Fig. 4 shows the spectrum of the detected signal. A signal/noise ratio of ~28dB in a 62.5mHz bandwidth was observed, which corresponds to a minimum detectable dynamic strain of ~1.5μstrain/√Hz. Although the resolution achieved using this demodulation scheme is smaller than the one obtained using some other demodulation schemes (the extreme case being the interferometric technique), it is still sufficient for many important applications, such as in smart structures. Also, it is relevant to emphasise that the resolution achieved with the demodulation technique presented here can be, to some extent, tailored to the application envisaged via design of the BFF, i.e. acting on its wavelength oscillation period and extinction ratio. Similarly to other FBG demodulation schemes, the concept proposed here can be used to interrogate several sensors combining it with standard fibre sensing multiplexing schemes (for example, time division multiplexing).

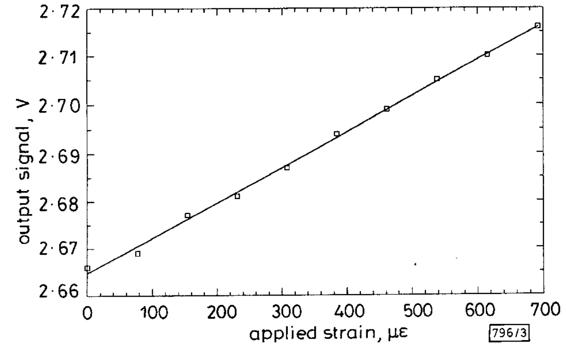

Fig. 3 *Sensor output voltage against induced axial strain*

$V_{out} = 2.6648 + 7.3906 \times 10^{-5} \times \text{strain}$; $R = 0.99884$

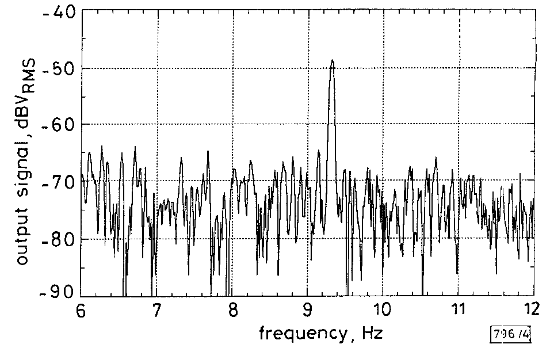

Fig. 4 *Signal/noise ratio measurement for an applied 7.8μstrain amplitude signal*

Bandwidth = 62.5mHz

In conclusion, we have demonstrated a simple technique for detecting Bragg wavelength shifts by using a biconical fibre filter. The filter had an unambiguous range of ~20nm with an extinction ratio of ~8dB. Static and dynamic strain resolutions of ~±3.5 μstrain and 1.5μstrain/√Hz were obtained, respectively.

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A.B. Lobo Ribeiro, L.A. Ferreira, and J.L. Santos (*Grupo de Optoelectrónica, INESC, R. José Falcão 110, 4000 Porto, Portugal*)

M. Tsvetkov (*General Physics Institute, Russian Academy of Sciences, Moscow, Russia*)

J.L. Santos: Also with Lab. Física, Universidade do Porto, Praça Gomes Teixeira, 4000 Porto, Portugal

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