index difference and \( d = 12.5 \mu m \) the separation of the fibre axes. The fibre modal parameters are \( U = \rho k^2 n_o^2 - \beta^2 \), \( W = \mu k^2 n_o^2 - \beta^2 \), \( V = (U + W)^{1/2} \) where \( n_o \) is the index of the cladding, \( n_i \) is the index of the surrounding medium, \( \beta \) the propagation constant and \( k \) the free-space wavenumber. The slight difference between the core and cladding indices is ignored in this calculation.

From the plots of \( \Delta \) in Fig. 2 it can be seen that a typical tapered cladding radius of 4 \( \mu m \) with \( \Delta > 0.5 \% \) the beat-length (twice the coupling length) will be effectively infinite (>25 cm) compared to the length over which the cores are closely spaced (>nm) (see loss Section below). It should be noted that this coupling reduces further as \( d \) increases.

**Fig. 2** Plots of beatlength in centimetres against tapered single-core fibre cladding radius in micrometres for various values of relative index difference between the cladding and surrounding medium in Fig. 1

Fibre cladding index of 1.447 is for silica at 1.3 \( \mu m \).

**Splicing:** We assume that the tapered connector is butted against the twin cores so that the respective axes are aligned. If we ignore offset and tilt losses, these losses arise from the mismatch between the indices and core sizes, and reflection from the splice. The former is negligible if the spot size of the singlemode fibre matches that of one of the cores of the twin-core fibre. Given the refractive-indices and core size of the singlemode fibre, the appropriate choice of relative index difference and core size for the singlemode fibre can be accurately quantified within the Gaussian approximation. The splice loss may then be simply expressed as

\[
\left( \frac{S_1 - S_2}{S_1 + S_2} \right)^2
\]

where \( S_1 = \rho_1 (2 \ln V_1)^{1/2} \) and \( S_2 = \rho_2 (2 \ln V_2)^{1/2} \) and where \( (\rho_1, V_1, \rho_2, V_2) \) apply to the tapered single-core and twin-core fibres, respectively.

It can be shown that the splice loss (excluding reflection losses, see below) to a core of any given twin-core fibre may be made arbitrarily small simply by matching the mode field diameters of the connector and twin-core fibre. Similarly, by using different diameter input fibres, low-loss splices can be made to twin-core fibres with nonidentical cores.

**Loss:** Tapering of the two fibres in the connector introduces loss through coupling of the fundamental mode to higher-order modes propagating in the cladding and the lower-index surrounding medium. A simple criterion gives an approximate upper bound on the local taper angle at each point along the taper for negligible loss, and simple estimation suggests that a low-loss connector with a taper length a few millimetres should be achievable. Simple plane-wave analysis suggests a maximum reflected power of \(-40dB\) provided the cores are aligned.

**Conclusions:** We have outlined the practical basis and theoretical justification for a fibre connector for low-loss coupling from single-core to multicore fibres. The device should have a low insertion loss, with negligible crosstalk and backreflection. Similar low-loss connectors for multicore fibres with a larger number of cores should also be feasible. Work is in progress to demonstrate this device experimentally.

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S. B. POOLE
Optical Fibre Technology Centre
University of Sydney
Sydney NSW 2006, Australia
J. D. LOVE
Optical Sciences Centre
Australian National University
Canberra ACT 2601, Australia

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**FIBRE OPTIC pH SENSORS PREPARED BY SOL-GEL IMMOBILISATION TECHNIQUE**

**Indexing terms:** Glass, Optical fibre

An improved fibre optic sensor with extended lifetime for pH measurements has been developed. The sensor is based on the absorbance change of organic indicators immobilised in a silica matrix coated as a thin film onto a porous glass optical fibre by the sol-gel technique. This approach has allowed the development of a highly stable, chemically durable and ruggedised fibre optic pH sensor. The sensor also has potential application in aqueous solutions at high temperatures and in those containing organic solvents.

**Introduction:** Continuous pH measurements remain important in a number of applications, such as the detection of environmental pollutants, chemical process control and the study of physiological systems. Fibre optic pH sensors can possess significant advantages over conventional, commercially available micro-pH electrodes because the optical signal is not subject to electromagnetic interference. In addition, the measurement can be performed by a single optrode without the secondary reference detector typically required by...
electronically-based devices. Optical sensors also offer good mechanical flexibility, very small size, low cost, safety and more precise measurement of extreme values of pH.

Most present generation fibre optic chemical sensors use polymers as a substrate to immobilise optically active organic indicators. However, these devices often exhibit significant degradation in the presence of organic solvents, strong acids or strong bases. Moreover, they also are less tolerant of the high temperatures or pressures typically encountered in many industrial and practical applications.

The sol-gel technique for immobilising fluorescent chemical indicators in a highly durable matrix has been used as a successful approach by Badini et al. and MacCraith et al. The motivation of the current research was to develop a durable and environmentally ruggedised fibre optic pH sensor which relies on absorbance changes. This report describes the use of the sol-gel technique as a generic method for immobilising absorption type pH indicators in a glass matrix to yield a stable, reversible and highly sensitive pH sensor. To achieve high resolution and sensitivity, a silica-gel immobilised with pH indicators was coated as thin film into a porous silica fibre substrate. A high surface area in the region of inline interaction between the analyte and the indicators causes a significant change in optical signal with pH level.

In principle, this technique can be applied to any organic indicator having a molecular size larger than that of the glass former (silica in this case) where it is trapped in the 'cage' formed by the silica ring structure. In this work, bromocresol purple and bromocresol green were employed as pH indicators. The dynamic pH range of these indicators is 3.5-5.4 and 5.2-6.8, respectively.

Experiment: A porous glass fibre was prepared by chemically leaching a small section (1 cm) of a phase-separated sodium borosilicate glass fibre prepared using methods previously described. Using a sol-gel technique outlined in Fig. 1, the porous section was coated by silica gel co-immobilised with the two selected indicators in a 1:1 molar ratio.

The optical glass fibre with the porous sensor section was mounted in an environmental test chamber that allowed access to solutions of different pH values. In this work, bromocresol purple and bromocresol green were employed as pH indicators. The dynamic pH range of these indicators is 3.5-5.4 and 5.2-6.8, respectively.

Results: Typical transmission spectra against pH level of the fibre optic sensor prepared by immobilisation of bromocresol purple and bromocresol green using a sol-gel technique are shown in Fig. 3. The sensor was evaluated at pH levels of 3.0, 5.0, 7.0 and 9.0 by injection of buffer solutions (Fisher Scientific Co.) into the testing chamber. The results show good sensitivity at all pH levels and represent the widest dynamic range that has been reported to date for fibre optic pH sensors. This range could in principle be extended further by combining different pH indicators, as long as the pH sensitive range of the indicators matches appropriately. The most sensitive measurement wavelength of the present sensor is 610 nm, which lies between the optimum sensing wavelengths of the two indicators in their aqueous solutions: 616 nm for bromocresol green and 588 nm for bromocresol purple, respectively.

Fig. 3 illustrates the dynamic response and reversibility of the sensor when exposed to solutions of pH 3 and 8. An excel-
lent response time of only a few seconds has been achieved for this particular sensor by controlling the pore size of the porous glass and optimizing the thickness of the silica gel film coating. Exposing the sensor in water for up to several days did not impair the stability or calibration of the indicators during subsequent optical measurements. In addition, the porous fibre optic pH sensor treated by the sol-gel technique can be employed for pH measurement in solutions containing organic solvents, which usually degrade or destroy polymer-based sensors. For example, the pH-sensitive silica gel showed very good stability and sensitivity to pH changes in organic solvents such as benzene, methylene chloride and alcohol. Its potential usefulness and survivability in high-temperature pH environments was also demonstrated by heating the sensor to 200°C for 2h without a resultant loss in the response of the sensor to pH changes.

**Fig. 4** Response curve for porous glass fibre co-immobilised with pH indicators of bromocresol purple and bromocresol green by sol-gel thin film coating

Temperature - 25°C

**Conclusion:** We report the development of a new fibre optic pH sensor that uses a porous glass optical fibre and a sol-gel immobilisation technique. The sensor is stable and reversible, with a wide dynamic range (pH 3-9) and short response time. Advantages of this new type of sensor over existing polymer-based sensors include its potential application for pH measurement in solutions containing organic solvents and high-temperature environments.

J. Y. DING
M. R. SHAHRIARI
G. H. SIGEL, JUN.

Fiber Optic Materials Research Program
Rutgers-The State University of New Jersey
Piscataway, NJ 08854, USA

**References**

**Fig. 1** Schematic diagram of reflection type ultrasonic correlation system introducing frequency multiplication method

**Introduction:** The measurement of sound velocity provides a clue to the physical properties of materials such as the mechanism of absorption, structure and relaxation. Recently, the reflection type ultrasonic correlation system for use in V/UHF ranges and at 5 MHz were developed for the accurate measurement of sound velocity. In this Letter a novel ultrasonic correlation system introducing a frequency multiplication method for velocity measurements at 5 MHz is described. The measurement principle and the equipment used are detailed and the effectiveness of the system is demonstrated through the experiments.

**Principle and apparatus:** Fig. 1 is a schematic diagram of the system. Burst pulse, generated by the continuous wave generator (CW gen), frequency divider (f div) and gate circuit (gate),...