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Sitzung 9/Session 9

Optische Meßwertaufnehmer und ihre Anwendungen
Optical Sensors and their Applications

Vorsitzender/Session Chairman
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9.1 Glasfaser-Meßwertaufnehmer und ihre Anwendungen

Optical Fibre Transducers and Applications

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Abstract

Light travelling in an optical fibre may be directly modulated by external parameters such as pressure, strain, temperature, etc. Thus the fibre may form the basis of a transducer involving neither moving parts nor electrical connections. Another class of transducers uses the fibre as a means of guiding light from a monitoring point to the measuring point where the light is externally modulated. This paper presents an overview of the current status of optical fibre sensors and discusses their future potential.

1. Introduction

The potential application of optical fibres as transducers has only been recognised within the last decade (1,2,3). However, a considerable amount of research and development work has been completed over the last five years, and it is the aim of this paper to review this work and examine the true potential of the fibre sensor.

There are a number of potential advantages in the use of fibres as sensors. The most obvious is the lack of electrical bias at the sensor, thereby removing electromagnetic interference problems and numerous safety considerations for operation in hazardous areas. The fibre is a low inertia transducer, which allows it to respond to stimulus changes over a very wide frequency range. It is chemically inert, and can transmit over a very long distance (∿km) without serious attenuation. There are other possibilities, as yet unexploited, which include the use of optical signal processing techniques to provide passive "smart sensors" and multiplexing architectures which will allow both sensor and data transmission channels to use the same fibre path.

The applications of fibre optic sensing diverge over a large range. Microphones and hydrophones have received much attention (4,5,6) and the fibre optic gyroscope (8,9) is probably the other principal research topic at present. Fibre sensors have also been reported to measure strain (10), temperature (11), magnetic fields (10) and acceleration (13). There is also considerable activity, little reported in the literature, in developing other simpler sensors for use in immediate applications.

This paper reviews the basic principles of light modulation in fibres and continues to describe in more detail, a few specific systems. It will become apparent that there is considerable scope for the development of simple but very effective transducers as well as more complex systems relying on advanced optics. Finally some of the more advanced future concepts are described, and the applications potential is discussed. The overall conclusion is that a wide range of optical fibre transducers are feasible with current technology, but many of the more advanced devices await the arrival of suitable components (many of which are currently under investigation by PTT operators) using both fibre and integrated optic building blocks.

2. Modulation of light in optical fibres

A light beam can be modulated in five of its basic properties, intensity, phase, polarisation, wavelength and spectral distribution. Most fibre sensors utilise the first three, though there is considerable potential in exploiting the last two. It is useful to consider briefly the optical requirements for all of these.

2.1 Intensity sensing

The modulation process is effected either by bending the fibre (14,15) or by introducing some form of shutter which moves across the fibre. This may be either due to relative motion of the fibre or to motion of a mask or reflector relative to fixed fibre ends.

The principal complication from these systems results from the fact that optical sources are all prone to intensity drift with aging and so a reference channel is always needed. These can usually be designed into the system with a little ingenuity.

2.2 Phase modulation

Detection of optical phase changes offers a means of measuring very small variations in physical parameters. Detection of optical phase must be performed interferometrically, which implies that a stable reference is required. The basic arrangement of one interferometer (the Mach Zehnder) is shown in Figure 1. In the heterodyne form, the Bragg Cell provides a frequency shifted reference beam and the phase shift is detected at the difference frequency. This is usually the most convenient form of the interferometer, though a homodyne version with a complex feedback bias arrangement has been described. (16)

Phase modulation schemes also require a coherent source, which must be a laser. HeNe gas lasers are the most convenient and economical, though semiconductor lasers (17,18) may be used, but with due caution. Finally it should be mentioned that interference only occurs between waves of similar polarisation, and changes in the output polarisation state from the fibre will alter fringe contrast, and thus either the SNR - for the heterodyne interferometer - or the calibration for the homodyne system.

The preceding discussion has also implied the use of monomode optical fibre, with consequent mechanical constraints (the core of a monomode fibre is only a few microns in diameter). The mechanical problem is eased in multimode fibres, and both heterodyning (19) and homodyning (20) interferometers have been investigated using multimode fibre in the single arm. These systems replace the alignment of single mode interferometers with a fading and signal distortion problem and a complete lack of any sensible low frequency capability.

A third multimode phase sensitive system exploits the "Fibredyne" process. This is very simple but is difficult to both linearise and stabilise. However, it has been used as the basis of both a direct (22) measuring flowmeter and a vortex shedding meter (23).

2.3 Polarisation

Variations in light polarisation are difficult to interpet in optical fibre transducers, since the fibre is often itself inherently birefringent and this birefringence varies with time. However, with special fibres (24), sensors which rely on detecting polarisation variations can be built. The principal application is in measuring Faraday rotation induced by a magnetic field produced by a large (∿100A) electric current. The basic detection scheme (25) is shown in Figure 2. Faraday rotation simply produces a polarisation rotation in the fibre proportional to the magnetic field produced by the wire. The variation is easily detected, and provided that the only variation is that due to magnetic fields (hence the special fibre) then a very successful sensor can be - and has been - constructed.

2.4 Wavelength modulation

One form of wavelength modulation is simply Doppler shift which may be produced by, for instance, backscatter from moving particles at the end of the fibre. This forms the basis of the fibre optic Doppler anenometer (25). This does, of course, require a coherent source.

A more general form of wavelength modulation may occur when, for instance, incoherent light is transmitted along a large core fibre to phosphorescent material, any light emitted from the phosphor is at a different wavelength. The wavelength and/or intensity of this return light will be a function of the parameter to be measured, and hence remote monitoring may be performed. Clearly much depends on the stability of both the light source and the phosphor (Figure 3).

2.5 Wavelength distribution modulation

There is obviously an overlap between wavelength modulation and wavelength distribution modulation. The latter implicitly requires that white light (or at least broadband illumination) be transmitted along a large core fibre to the sensing region. Here it is modulated by a filter which alters its spectral band pass characteristic with variations in the parameter to be measured. The spectrum of the return light is analysed and subsequently related to the initial parameter.

Note that some form of spectrometer is now required, and this may take several forms. The PTT industry is interested in wavelength multiplexing devices (26,27) which may be immediately exploited here. Similarly a very simple prism or grating spectrometer is readily assembled. It is even possible to use the fact that the change in return spectrum will produce a change in amplitude on the photodetector by virtue of the latter's inherent filtering properties.

2.6 Discussion

This section has then summarised the available techniques whereby light guided by an optical fibre may be modulated and some of the means whereby that modulation may be detected. Interferometric techniques are doubtless the most complex, but offer probably the most potential. However, simple intensity and/or wavelength modulation provides the basis of a large variety of sensing functions. Some specific examples of transducer investigated to date follow.

3. Examples of specific sensors

This section will indicate the diversity of functions which may be performed by optical fibre sensors. It is by no means an exclusive account!

3.1 Vernier positional indicator

A possible configuration for an optical fibre position sensor is shown in Figure 4. This is essentially a vernier device where a line of nine input fibres illuminates ten output fibres. With appropriate attention to the input and output fibre spacing, resolutions of the order of 0.05% of the fibre diameter should be attainable by suitable processing of the output intensities. Some computational facility should be available to compensate for component drifts. This device is as yet undeveloped but a much simpler device, a strain gauge "tell tale" (29) using an array of variable breaking strain fibres is at the prototype stage.

3.2 Optical fibre microphone

Numerous schemes have been suggested to realise an optical microphone. These schemes come into two categories, those using modulated reflection or transmission and those using phase modulation (see section 3.3).

A very simple, but effective, reflection modulation microphone - suitable for use in telephony - uses the principles shown in Figure 5 (30). Movement of the diaphragm modulates the amount of light reflected back along the illuminating fibre, and performance acceptable for telephony has been achieved. It is interesting to note that sufficient optical power (a few milliwatts) can be transmitted along the fibre from an exchange to a subscriber to sound an audible alarm at the subscriber's end, so that all optical telephone links do become feasible. An alternative scheme, based on frustrated internal reflection has recently been proposed (31).

There are many other techniques available. One reflection technique (32) uses a central illuminating fibre surrounded by six return fibres. Sub-nanometre resolution is claimed for displacement of the reflector along the fibre axis.

3.3 Phase sensitive acoustic sensors

The phase of light passing along an optical fibre may be varied by changes in environmental parameters such as pressure, temperature or strain. The phase sensitivities, per metre of fibre, are of the order 100rads/^{o}C, 10/rads/bar (1 bar = $1.018 \times 10^5 N/m^2$) and 10rads/microstrain.

Phase detectors can, quite readily, be made to detect 10^{-4} radians, and with care, 10^{-8} radians sensitivity can be achieved.

Optical fibre hydrophones may be readily fabricated from a coil of single mode fibre. (Multimode fibre may also be used with some penalties in noise and stability). This fibre forms one arm of a heterodyning Mach Zehnder interferometer, and sensitivities superior to piezoelectric devices have been reported (33). The sensitivity may be varied by using specially coated fibres (34), but there remain a number of problems. The sensitivity of the hydrophone should increase linearly with interaction length, but our own measurements have shown a saturation effect. There is also a significant problem in that the fibre leading to and from the hydrophone is itself acoustically sensitive, and this length may often exceed the length of the fibre in the hydrophone proper. There are several suggested solutions to these problems but the possibilities are as yet not completely evaluated.

3.4 The optical fibre gyroscope

The optical fibre gyroscope is based on exploitation of the Sagnac effect, originally described more than half a century ago (35). The basic principle is shown in Figure 6. Light from the laser is split into two equal components launched in opposite directions into the fibre loop. If the loop is rotated, then light travelling with rotation will remain in the fibre for a slightly longer time than light travelling in the opposite direction.

An intuitive theoretical description of the gyroscope gives the phase difference $\Delta\phi$ between the two emerging beams as

$$\Delta\phi = \frac{4\pi L R \Omega}{\lambda_o c}$$

which is the non-relativistic limit of the device characteristics. The fibre gyro could be an inexpensive, fairly low quality disposable device or, perhaps in the future, a high sensitivity but complex, inertial navigation instrument. Current experimental performance figures attain a sensitivity of the order of 1^o/hr, (36,37) though it is theoretically possible to obtain significantly better performance. Detailed understanding of the system physics is still incomplete (38), and doubtless future improvements in system configuration and component design will achieve orders of magnitude higher sensitivity levels.

3.5 Thermometric probes

Optical fibres may form the basis of a wide variety of thermometric probes, many of which can be so tiny they may be inserted into a hyperdermic needle. Interferometric probes have as yet been relatively unsuccessful due, ironically, to excessive sensitivity. Recently, single fibre interferometers using the temperature dependence of differential delay between orthogonally polarised modes in birefringent fibre (31) as indicated schematically in Figure 7, offer potential solutions.

The most promising thermometric probes are the self luminescent and phosphorescent (41) types as shown schematically in Figure 3. Observation of temperature dependent delay time of phosphorescence is the essential principle of the latter, while the former may even be implemented on the basis of measuring black body radiation coupled into the fibre. In both cases, rugged, compact and accurate fast response thermometers may be fabricated.

3.6 Discussion

The preceding examples have barely scratched the surface of optical fibre sensors. However, the principal modulation techniques have been illustrated. The design of a real transducer reduces to the engineering problem of enhancing the modulation sensitivity to the required parameters and reducing its sensitivity to other parameters. Successful solutions to these problems will involve research into materials, optical architectures and electronic and optical signal processing.

For the wide variety of intensity modulation sensors, the required development falls more into the realm of transducer engineering development than optics research, and much has already been achieved on this basis. The general conclusion, bourne out in our own experiments and other laboratories is that intensity sensors can themselves be remarkably sensitive to within two order of magnitude or thereabouts of that attainable with interferometric devices (42).

Most coherent (interferometric) sensors are at a relatively early stage in their development (43). It is only recently (August 1981) that the US Naval Research Laboratory (44) tested a prototype ruggedised optical fibre hydrophone. This device, sketched in Figure 8, functioned very well, but note that it does require a power supply and that the output from the hydrophone is electrical. The optical fibre lead sensitivity to and from the sensor remains a problem and the NRL prototype is recognised as an intermediate step to the true all fibre interferometric sensor. The Sagnac interferometer is the only current truly self compensating arrangement, and even this must be carefully adjusted with respect to launch and receive polarisations. The Sagnac configuration is clearly capable of detecting parameters other than rotation, and recently (45) use of the fibre ring interferometer as an alternative current measuring device has been reported. It should also be noted that the Faraday rotation current sensor (24) has enjoyed considerable success and prototype production devices are currently under construction.

4. Future prospects

It will probably be some time before the full potential of optical fibre sensors is realised. There will be inevitable engineering development of intensity based sensors to take them into the real market-place, but exciting conceptual advances remain to be made in the realm of interferometric sensors at the component level and in all optical sensors at the system level.

A number of important component developments currently under way will greatly influence the future of interferometric fibre sensors. These include several investigations into enhancing the stability of single mode semiconductor lasers using analogues to phase lock loops and similar configurations (46,47). These may be either used to lock the laser frequency or the error signal may itself provide the sensor output when the fibre forms, effectively, part of the laser cavity (Figure 9).

Birefringent fibres, and, more so, associated polarisation selective components will allow significant additional flexibility in sensor configuration. In particular, polarisation rotation could form the basis of a new family of lead insensitive, compact interferometric sensors. Initial simple estimates indicate that a strain gauge of total dimensions much less than 1mm could be readily fabricated. This device requires polarisation selective couplers, but should be within the scope of integrated optics processing.

This technology (integrated optics) (48) will play a necessary role in future PTT systems and the techniques thus developed will be directly applicable to interferometric sensing. It is likely that one form of the strain gauge would be as a fully integrated optic Mach-Zehnder (M-Z) interferometer, and indeed an integrated M-Z interferometer could be configured as a wide variety of sensors.

It is similarly likely that this technology will provide essential components such as local oscillator modules for heterodyne systems (49) and splitter, combiner and phase bias components for a variety of applications, most notably at present, the gyroscope (50).

Interface problems also require completely satisfactory solutions. Particularly from semiconductor laser to integrated optic waveguide, and from waveguide to fibre. Among the most promising approaches is the use of an anisotropically etched V groove in silicon as the locating jig from monomode fibre to monomode guide (51). Semiconductor lasers with lens-ended single mode fibres pigtailed permanently in place are now becoming available (52), and it seems likely that direct planar launch from lasers into integrated optics will similarly be soon available.

It is however at the system level that optical fibre sensors offer really significant advantages. Already, the geometrical flexibility of the fibre hydrophone allows for unique variations in polar and frequency response of underwater acoustic monitoring systems.

Numerous architectures have been suggested to allow multiplexing of many fibre sensors on to one fibre loop. and one of these is shown schematically in Figure 10. Variations include wavelength multiplexing and sensor operational frequency multiplexing. As a final step in the multiplexing chain, it is perfectly feasible to combine this sensor multiplexing with a Fibredyne (21) data link along the same fibre thus using the fibre path and component set to its utmost.

Finally, the fact that the optical medium is well suited to performing instantaneous Fourier related (53,54) signal processing on spatial signals has, to date, been completely ignored in sensing systems. This capacity can be used to encode spatial data, perhaps concerning the position of the reflector in an incoherent system, into another form - possibly digitised - by the use of suitable correlation filters. It may also be used to perform pattern recognition on to fault conditions or to change the form of the spatial data into a more readily recognised format - for instance a spectral representation.

Conclusions

This has been a wide ranging, and therefore often superficial, account of the prospects for optical fibre sensing. In the final reckoning, the eventual success of these techniques will depend on their position in comparison to other, often well established measurement techniques. Comparisons may be made in terms of cost, sensitivity and applications suitability. Present day sensors are remarkably, and necessarily, economic, but it does seem that both the sensitivity of fibre sensors and the applications flexibility will prove to be the attractive features. At present, fibre sensors are well suited to applications requiring spark-proof devices, for instance in petrochemical plant, even though sensitivities are probably comparable. In the future, multiplexed transducers on to the same fibre path, especially with a parallel data route, coupled with on-line instantaneous signal processing will offer unique flexibility to the system designer.

The possibilities are remarkable. The bounds are imposed only by the designer's imagination and, in some, but not all, cases by the limits of available technology. There is, without doubt, an interesting future for optical fibre sensors and systems.

References

1. Kingsley, S.A. and Davies, D.E.N., "The use of optical fibres as instrumentation transducers", CLEO, San Diego 26-27 May 1976, Digest of Technical Papers, p.24-25.

2. Vali, V. and Shorthill, R.W., "Fibre ring interferometer", Applied Optics, 15, 5, pp.1099-1100, May 1976.

3. Culshaw, B., Davies, D.E.N. and Kingsley, S.A., "Fibre optic strain, pressure and temperature sensors", Proc. 4th ECOC, Genoa, Italy, Sept. 1978. Proceedings published by IEE.

4. Bucaro, J.A. and Dardy, H.D., "Fibre Optic Hydrophone", J.Acoustic Soc. America, 62, 5, November 1977, pp.1302-1304.

5. Culshaw, B., Fiddy, M.A., Hall, T.J. and Kingsley, S.A. "Fibre optic acoustic sensors", Ultrasonics International 1979, Graz, Austria, May 1979, pp.267-272.

6. Bucaro, J.A. and Hickman, T.R., "Measurement of sensitivity of optical fibres for acoustic detection", Applied Optics, 18, 6, March 1979, pp.938-940.

7. Bohm, K., Marten, P., Petermann, K., Weidel, E. and Ulrich, R., "Low drift gyro using a superluminescent diode", Electronics Letters, 17, 10, p.352, 14 May 1981.

8. Bergh, R.A., Lefevre, H.C. , and Shaw, H.J., "All single mode fibre optic gyroscope", Optics Letters, 6, 4, p.198, April 1981.

9. Cole, J.H., Giallorenzi, T.G. and Bucaro, J.A., "Research update on fiber optics sensors", International Fibre Optics and Communication, 2, 2, p.23-25, March 1981.

10. Butter, C.D. and Hocker, G.B., "Fibre optic strain gauge", Applied Optics, 17, 18, pp.2867-2869, 15 September 1978.

11. Culshaw, B., "Fibre optic sensors", Proc. New Frontiers in Fibre Optics, Published by Engineers Digest, Wigmore St, London W1, May 1980.

12. Dandridge, A., Tveten, A.B. and Giallorenzi, T.G., "Interferometric current sensors using optical fibres", Electronics Letters, 17, 15, p.523, 23 July 1981.

13. Tveten, A.B., Dandridge, A., Davis, C.M. and Giallorenzi, T.G., "Fibre optic accelerometer", Electronics Letters, 16, 22, p.854-6, 23 October 1980.

14. Fields, J.N., Asawa, C.K., Ramer, O.G. and Barnoski, M.K., "Fibre optic pressure sensor", J.Acoustic Soc. Amer. 67, 816, 1980.

15. Harmer, A.L., "Displacement, strain and pressure transducer using microbending effects in optical fibres", XX Senate of URSI, p.383, August 1981, Washington DC.

16. Jackson, D.A., Priest, R., Dandridge, A. and Tveten, A.B., "Elimination of drift in a single mode optical fibre interferometer using a piezoelectrically stretched coiled fibre", Applied Opts, 19, p.2926, 1980.

17. Ball, P.R. and Culshaw, B., "Semiconductor laser sources for coherent optical fibre systems", IEE Journal on Solid State and Electron Devices, 3, 6, November 1979, pp.242-245.

18. Dandridge, A., Miles, R.O., Tveten A.B. and Giallorenzi, T.G., "Noise and spectral properties of single mode cw laser diodes", Digest of Technical Papers, 3rd IOOC San Francisco, April 1981, p.36. Published by IEEE.

19. Culshaw, B., Davies, D.E.N. and Kingsley, S.A., "Multimode optical fibre sensors", in Physics for Fiber Optics 2 published by American Ceramic Society.

20. Roychoudhuri, C., "Multimode fibre optic interferometry", Appl. Opts. 19, 12, pp.1903-1906, 15 June 1980.

21. Culshaw, B., Ball, P.R., Pond, J.C. and Sadler, A.A., "Optical fibre data collection", Electronics and Power, February 1981, p.148.

22. Culshaw, B. and Hutchings, M.J., "Optical Fibre Flowmeter", Elec. Letts., 15, 18, pp.569-571, August 1979.

23. Lyle, J.H. and Pitt, C.W., "Vortex shedding fluid flowmeter using optical fibre sensor", Elec. Letts., 17, 6, p.244, 19 March 1981.

24. Norman, S.R., Rayne, D.N., Adams, M.J. and Smith, A.M., "Fabrication of single mode fibres exhibiting extremely low polarisation birefringence", ibid, 1979, 15, pp.309.311.

25. Rogers, A.J., "Optical measurement of current and voltage on power systems", IEE Journal Electric Power Applications, 2, 4, August 1979, pp.120-124.

26. Dyott, R.D., "Fibre Optic Doppler Anenometer", IEE Journal Microwave and Modern Optics.

27. Conradi, J., Macuejko, R., Strauss, J., Few, I., Duck, G., Sinclair, W., Springthorpe, A.J. and Dyment, J.C., "Laser based WDM multichannel transmission system", Elec. Letts., 17, p.71, 22 January 1981.

28. Sullivan, P.J., Private communication, 1978.

29. Hockenhull, B., "Optical fibre tell tale", presented at Seminar on Structural Integrity Monitoring of Off-shore Platforms, IMechE, 13 April 1978.

30. Fromm, I. and Unyerberger, H., "Direct modulation of light by sound", Proc. 1978 International Optical Computing Conference pp.40-42, London, September 1978, published by IEEE.

31. Phillips, R.L., "Proposed fibre optic acoustic probe", Optics Letters, 5, 7, p.318, July 1980.

32. Cook, R.O. and Hamm, C.W., "Fibre optic level displacement transducer", Appl. Opts., 18, 19, p.3230-3241, 1 October 1979.

33. Shajenko, P., Flatley, J.P. and Moffatt, M.B., "On fibre optic hydrophone sensitivity", J. Acoustic Soc. Am. 64, 5 November 1978, pp.1286-88.

34. Ceilo, P.G., "Fibre optic hydrophones, improved strain configuration and environmental protection", Appl. Opts., 18, 17, pp.2933-2937, September 1979.

35. Sagnac, G., "L'ether luminex demontre par l'effet du vent relatif d'ether dans un interferometre en rotation uniforme", C.R. Acad. Sci. 95, 708-710, 1913.

36. Bergh, R., Lefevre, H. and Shaw, H.J., "All single mode fibre gyroscope", Digest of Technical Papers, 3rd 1OOC San Francisco, April, 1981, Published by IEEE.

37. See proceedings first International Conference on Fibre Optic Rotation Sensors and Related Technologies, Boston, 9-11 November 1981.

38. Giles, I.P. and Culshaw, B., "Performance Limitations of Optical Fibre Gyroscopes", to be published, IEE Proceedings H.

39. Eickoff, W., "Temperature sensing by mode-mode interference in birefringent optical fibres", Optics Letters, 6, 4, p.204, April 1981.

40. Dakin, J.P., private communication, 1980.

41. McCormack, J.S., "Optical Sensors using Luminescent Materials", XX Senate URSI, p.385, Washington DC, August 1981, see also Physics Today, July 1981, p.61.

42. Lagakos, N., Trott, W.J., and Bucaro, J.A., "Microbending fibre optic sensor design optimisation", Proc. CLEO 1981.

43. Culshaw, B., "Interferometric optical fibre sensors", to be published, Journal of the Institute of Measurement and Control.

44. Giallorenzi, T.G., private communication 1981, results of fibre optic hydrophone field trials to be published.

45. Arditty, H.J. and Spitz, E., "Interferometric fibre optic sensing of inertial rotation, magnetic fields and fluid velocity in the Sagnac configuration", XX Senate URSI, p.382, August 1981, Washington DC.

46. Cobb, K.W., MSc project report, University of London 1981.
Also
Cobb, K.W. and Culshaw, B., "Reduction of optical phase noise in semi-conductor lasers", submitted for publication.

47. Kikuchi, K., Okoshi, T. and Kawanishi, S., "Achievement of 1MHz frequency stability of semiconductor lasers by double loop AFC scheme", Electronics Letters, 17, 15, p.515, 23 July 1981.

48. Tien, P.K. and Giordmaine, J.A., "Building the integrated optical circuit", Optical Spectra, 15, 6, p.50, June 1981.

49. Cushaw, B. and Wilson, M.G.F., "Integrated optic frequency shifter modulator", Elec. Letts, 17, 3, p.135, 5 February 1981.

50. Papuchon, M., "Present applications of integrated optics", Digest of Technical Papers, 3rd IOOC, San Francisco, April 1981, p.68.

51. Sheem, S.K., Bulmer, C.H., Moeller, R.P., Burns, W.K., "High efficiency single mode fibre/channel waveguide flip chip coupling", Integrated and Guided Wave Optics Technical Digest, p.28-30, (NY USA 1980 IEEE).

52. Kayoun, P., Puech, C., Papuchon, M., Arditty, H.J., "Improved coupling between laser diodes and single mode fibre tipped with a chemically etched self-centred diffraction element", Elec. Letts., 17, 12, p.400, 11 June 1981.
Note: Laser diodes, New Brunswick, New Jersey USA offer laser diodes with single mode pigtails.

53. Goodman, J.W., "Introduction to Fourier Optics, McGraw Hill, 1968.

54. Gaskill, J.D., "Fourier Transforms, Linear Systems and Optics", Wiley 1978.

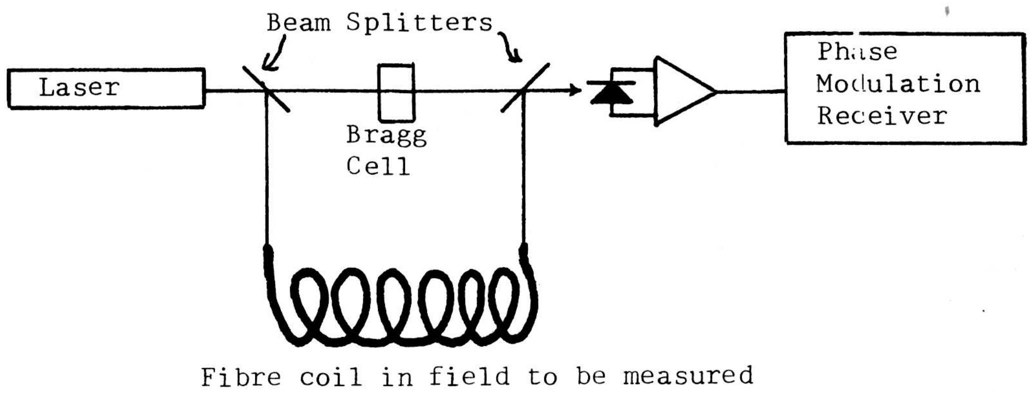

FIGURE 1: Basic Mach-Zehnder interferometer. The Bragg Cell causes a frequency shift of the laser beam passing through it, and hence this acts as a local oscillator. The phase modulation caused by the sensed field is then transferred to the intermediate frequency set by the Bragg Cell.

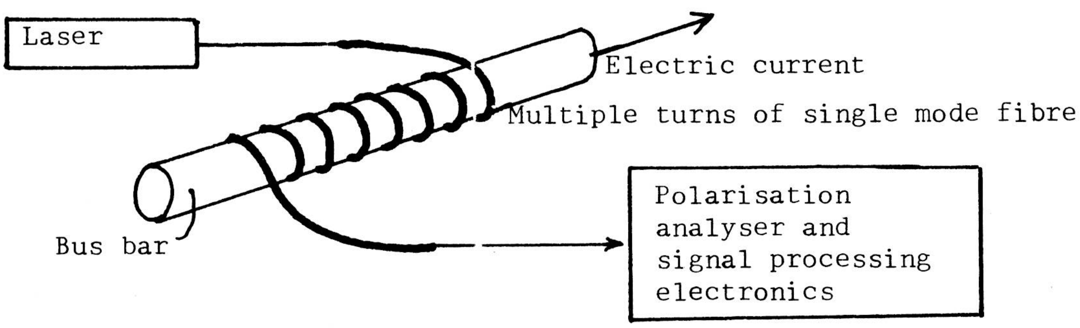

FIGURE 2: Schematic of a polarisation rotation current monitoring probe suitable for use in public utility applications. The laser injects linearly polarised light, and the output light is rotated in polarisation by the Farady effect in the silica fibre guide.