Advanced materials and techniques for fibre-optic sensing

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Abstract. Fibre-optic monitoring systems came of age in about 1999 upon the emergence of the world’s first significant commercialising company – a spin-out from the UK’s collaborative MAST project. By using embedded fibre-optic technology, the MAST project successfully measured transient strain within high-performance composite yacht masts. Since then, applications have extended from smart composites into civil engineering, energy, military, aerospace, medicine and other sectors. Fibre-optic sensors come in various forms, and may be subject to embedment, retrofitting, and remote interrogation. The unique challenges presented by each implementation require careful scrutiny before widespread adoption can take place. Accordingly, various aspects of design and reliability are discussed spanning a range of representative technologies that include resonant microsilicon structures, MEMS, Bragg gratings, advanced forms of spectroscopy, and modern trends in nanotechnology. Keywords: Fibre-optic sensors, fibre Bragg gratings, MEMS, MOEMS, nanotechnology, plasmon.

1. Introduction
Fibre-optic sensors now provide a critical addition to our arsenal of monitoring technology with global sales reaching $1.9bn pa [1]. From an almost zero baseline a quarter of a century ago, fibre-optic monitoring systems have seen revolutionary levels of research, development and commercial exploitation due, in part, to: the many well-known potential advantages that optical sensors have over traditional technologies, the availability of high-quality glass optical fibres, and the introduction of solid-state sources and detectors. The market in fibre-optic sensors now exceeds 2.5% of the total sensors market [2], and may grow by as much as 20% pa over the next 5 years [1].

2. Early exploitations: Sensing within harsh environments
The success story began in the late 1980s when various global players sought to establish optical sensor technology within niche application-areas supported by its inherent advantages.

2.1. Body scanning, chemical synthesis and electrical switchgear
Development and commercialisation of rugged polychromatic monitoring systems [3-4], for example, was initially promoted through successful showcase monitoring of:

- Respiration rate, blood oxygenation and temperature of patients undergoing body scans.
- Pressure within the production vessel for an explosive monomer.
- Contact travel within a high-voltage circuit-breaker.
- Pressure, temperature and dielectric strength of SF6 insulation.
2.2. Distribution transformers
The advent of Australian photonics in the early 1990s saw a massive initiative to promote fibre-optic sensors into the electric power industry, where a significant motivation was the need to measure “hot-spot” temperatures in distribution transformers.

2.2.1. Resonant microsilicon beams. A novel silicon undercutting process [5] creates a free-standing microsilicon beam that acts as one mirror of a reflective Fabry-Perot cavity, has high internal stress, and has a temperature-dependent resonant frequency.

2.2.2. Temperature sensing. Conversion of the microsilicon beam into a fibre-optic temperature sensor involves [6]:
- Placement under high vacuum: <10^{-2}mbar leads to resonance with a “Q-factor” exceeding 10^5.
- Optical excitation, and interferometric interrogation.
- Fourier-analysis of the interrogation signal, giving temperature resolutions of better than ±0.4°C.
- Attachment to the end of an optical fibre, and encapsulation within rugged packaging.

3. Fibre-optic microelectromechanical systems (MEMS)
While the focus is clearly on “optical” rather than “electrical”, the section 2.2.1 technology is sometimes called a microelectromechanical system (MEMS) – more specifically it is an optical MEMS [7] or MOEMS. Section 2.2.2 could then be deemed to be describing a resonant fibre-optic MEMS sensor. The R&D of such resonant sensors peaked shortly after the mid-1990s with no significant commercialisation.

However, the underlying microsilicon technology is of major significance because it helped fuel revolutionary growth in non-resonant fibre-optically addressed MEMS [8] and silicon-on-insulator (hybrid silicon) photonics [9-12]. Often exploiting interferometric methods of signal transduction, such technologies are used in both sensing and interrogation. Most importantly, being based on the generic and abundant MEMS technology, the market for fibre-optic MEMS sensors is opened-up far beyond the original harsh-environment applications.

3.1. New trends in sensing
New forms of sensing structure are similar to those discussed in sections 2.2.1- 2.2.2, but they are not resonant, and thus do not need evacuation. A simple pressure (or strain) sensor is possible by configuring one end of the Fabry-Perot cavity as a diaphragm (or translatable) surface [13]. Reconfiguring the Fabry-Perot cavity enables other measurands – for example; temperature by the inclusion of a birefringent crystal [14], and refractive index by opening-up the cavity to the surroundings [15].

3.2. New trends in interrogation
While there are numerous initiatives towards fabricating individual MEMS components – such as mirrors [16], filters [17] and gratings [18] – the UK’s collaborative AIMS project (2002-2005) was, perhaps, the first significant attempt to integrate all interrogation functions on to a single silicon-on-insulator (SOI) chip. This project developed an electrically-activated Fabry-Perot-based MEMS interrogating filter and associated SOI circuitry [19-20].

The processing of Fabry-Perot signals is a significant challenge impeding widespread acceptance due to the problems of the 2π-phase ambiguities and signal drift. Numerous approaches have been taken: the older ones being quadrature based methods [21] and the use of two interrogating wavelengths [22], and the newer ones being Fourier based methods [23] and low-coherence (white light) interferometry [24].
An exciting new alternative to Fabry-Perot based MEMS is the possibility of interrogation using microring resonators [25].

3.3. Comments on performance
Fibre-optic MEMS devices can be small – Opsens Inc., for example, is marketing pressure and temperature sensors with outside diameters respectively of 0.25 mm and 0.17 mm. Due to the small size of optical MEMS, the frequency response of pressure sensors can reach 80 kHz, and the response time of temperature sensors can be as short as 10 ms. As with the packaging of any Fabry-Perot device, it is important to use epoxy-free bonding to avoid signal distortions caused by adhesive expansion. Some form of low-coherence (white light) based interrogation seems to be the most acceptable solution to \(2\pi\) phase ambiguities and signal drift. A number of other issues may need to be addressed such as fatigue-induced crack-growth, creep under constant stress, material deformation (due to annealing and other factors), anodic oxidation, and robustness to environmental factors (such as vibration).

4. Fibre-Bragg-grating
As a disruptive technology, the significance of the fibre-Bragg-grating (FBG) should not be underestimated – it immediately superseded more-complex sensing technologies and catapulted fibre-optic sensors into areas hitherto the domain of traditional technologies, notably thermometers and strain gauges. An FBG [26] is a narrow-band reflection filter created by inscribing a periodic variation in refractive index within the core of an optical fibre. This index variation is perturbed through a change of temperature or strain, leading directly to a change in the reflected so-called Bragg wavelength. Due to the encoding of the Bragg wavelength, FBGs may be used as temperature and strain sensors. Other parameters may be measured if they can be transduced to temperature or strain.

Backed by continuing collaborations and research output, the industry has matured with a number of global players positioned in the military, aerospace, civil engineering, energy, environmental, medical and other sectors [27-29].

4.1. FBG temperature sensing
Through early application of the FBG-temperature sensor to transformer “hot-spot” monitoring [30], the Australians quickly superseded their own work on resonant microsilicon sensors (sections 2.2.1-2.2.2)

4.2. FBG strain sensing
In terms of strain sensing, big breaks came in the form of two show-case collaborations, specifically the UK’s MAST (1995-98) and SHODOS (1996-1998) projects. While the former project monitored the flexing of composite yacht masts; the latter monitored long-term strain in civil engineering structures such as bridges, representing the technology’s first foray into Structural Health Monitoring. As sensors, FBGs may be retrofitted (as in SHODOS) or embedded, as in the exciting and highly active field of Smart Structures.

5. High-power systems
High-power systems are of importance in at least the following two situations. Powers up to about 1W are used in optically-powered hybrid systems, which feature fibre-optic activation of conventional electronic sensors [31]. At still-higher power, a 1.9W 1651nm Raman amplifier system with wavelength-tuneable output has been showcased by researchers at Gooch and Housego PLC for remote spectroscopic measurements of methane leaks.

6. Key new technologies and abilities
In addition to MEMS, there are a number of major developments that could help spark a second revolution in fibre-optic sensors:
FBGs can now be inscribed at predetermined locations as the fibre is being drawn; thus avoiding any post-processing damage, and facilitating realisation of their great multiplexing capability.

FBGs can now be written point by point, so that FBGS of arbitrary profile can be inscribed.

Tilted fibre Bragg gratings may offer self-referencing, multiparameter physical sensing, as well as plasmonic applications.

Plasmons, themselves, are waves that tend to propagate along the surface of metallic and certain dielectric materials. Such waves are highly sensitive to any changes in the refractive index of the material as well as the device’s geometry, and may offer great potential in fibre-optic sensing applications.

Optical fibre is available which has two mobile cores mounted in close proximity. Such fibre has unique transmission properties that may be useful in sensing.

Nanotechnologies look set to offer enhanced sensing opportunities when used in conjunction with optical fibres.

Nanogratings, in particular, may offer enhanced sensing and spectrometry.

Fibre-modal interferometers offer the promise of highly sensitive sensors.

Photonic crystal fibres may enhance many of the above opportunities.

7. Discussion and conclusions

At least the first generation of fibre-optic monitoring systems has come age of with the establishment of Bragg-grating based sensor technology. Such gratings can be inscribed at any locations at the time of fibre-manufacture (preserving its pristine strength), can have different Bragg wavelengths, can directly sense temperature and strain, and be subject to wavelength-demodulation based interrogation schemes. Some challenges remain such as simplifying the currently labour-intensive methods of installation, ensuring faithful strain transfer from the substrate to the grating, and efficiently separating out the dual temperature/strain dependencies. Despite these challenges, the FBG sensors are likely to remain the dominant contributor to the expected near-term 20% pa growth in the fibre-optic sensors market.

Particularly active within the market are interferometric sensors, for a variety of measurands, based on the Fabry-Perot cavity. Such devices are largely configured as reflective point-sensors; an important category of implementation. However, as such, they will not achieve the multiplexing convenience of the FBG.

Configurable in both sensing and interrogating forms, fibre-optic MEMS is one of a number of technologies that is likely to shake up the market in manner akin to the FBG. It holds the promise of cheap, mass-produced, miniaturized devices, principally by borrowing processing technology from the established silicon-on-insulator MEMS market. Sensors are typically based on the Fabry-Perot cavity, and a number of configurations are available for pressure and other measurands. Development of fibre-optic MEMS interrogators continues. Individual components have been made, but the completely integrated silicon-photonic interrogation system remains elusive due, in part, to silicon’s indirect bandgap hindering its use as an emitter.

In the absence of a completely integrated solution, much interrogator development continues. Commercial activity is intense, as evidenced by the number of players, and the rate at which new/improved/cheaper interrogation systems are brought to the market place. Such systems range from bulk-optic affairs, incorporating spectrometer-type devices, to more miniaturized forms that include MEMS components, wavelength scanners and filters.

Also set to revolutionise the market in the next couple of decades are fibre-optic devices based on nanotechnology, photonic crystal fibres and surface plasmons.
8. References

[1] 2013 Fiber Optic Sensors Global Market Forecast (Aptos: ElectroniCast Consultants)

[2] 2013 Global Markets and Technologies for Sensors (Kirkland: Electronics.ca Publications)

[3] 2008 Chromatic Monitoring of Complex Conditions ed G R Jones et al (London: Taylor & Francis)

[4] Wiszniewski W 1997 United States Patent 5,682,053: Silicon Transducer with Composite Beam (Alexandria: USPTO)

[5] Henderson P A, Henderson P H and Wiszniewski W R 1996 Frequency-Encoded Temperature Sensor using Interferometric Microresonators: ACQFT96 Proc. 21st Australian Conf. on Optical Fibre Technology (Conrad Jupiters, Gold Coast, Queensland, 1-4 December, 1996) (Milsom Point: IREE Society) pp 282–285

[6] Piyawattanametha W and Qiu Z 2012 Optical MEMS, Microelectromechanical Systems and Devices ed N Islam (New York: Intech) pp 291–330

[7] Pang C, Yu M, Zhang X M, Gupta A K and Bryden K M 2012 Multifunctional optical MEMS sensor platform with heterogeneous fiber optic Fabry-Perot sensors for wireless sensor networks Sensors and Actuators A 188 471–480

[8] Rickman A G, Reed G T and Namavar F 1993 Silicon-on-Insulator Optical Rib Waveguide Circuits for Fiber Optic Sensors: Proc. SPIE 2071 Distributed and Multiplexed Fiber Optic Sensors III ed A D Kersey and J P Dakin (Boston, 30 December, 1993) (Bellingham: SPIE) pp 190–6

[9] Noell W 2002 Applications of SOI-based optical MEMS IEEE J. Sel. Topics Quant. Electron. 8 148–54

[10] Jalali B and Fathpour S 2006 Silicon photonics J. Lightwave Technology 24 4600–4615

[11] Heck M J R, Bauters J F, Davenport M L , Doylend J K, Jain S, Kurczevile G, Srinivasan S, Tang Y and Bowers J E 2013 Hybrid silicon photonic integrated circuit technology IEEE J. Sel. Topics Quant. Electron. 19 6100117

[12] Ge Y and Wang M 2008 Optical MEMS pressure sensor based on a mesa-diaphragm structure Optics Express 16 21746–52

[13] Duplain G and Neste R V 2007 United States Patent 7,265,847: Birefringent Optical Temperature Sensor and Method (Alexandria: USPTO)

[14] Tian Y, Wang W, Wu N, Zou, Guthy C and Wang X 2011 A miniature fiber optic refractive index sensor built in a MEMS-based microchannel Sensors 11 1078–87

[15] Saitoh T, Nakamura K, Takahashi Y and Miyagi K 2005 High-Speed MEMS Swept-Wavelength Light Source for FBG Sensor System: Proc. SPIE 5855 17th International Conference on Optical Fibre Sensors Ed M Voet et al (Bruges, 23 May, 2005) (Bellingham: SPIE) pp 146–9

[16] Beccherelli R, De Gio L, Umerton C, Donisi D, d'Alessandro A and Caponero M A 2008 Fiber Bragg Grating Interrogation System Based on a Novel Integrated Optical Filter: IEEE Sensors (Lecce, 26-29 October, 2008) (Washington: IEEE) pp 140-3
[17] Xiao G, Mrad N, Guo H, Zhang Z and Yao J 2008 A planar lightwave circuit based micro interrogator and its applications to the interrogation of multiplexed optical fiber Bragg grating sensors Optics Communications 281 5659–63

[18] Ang M T W, Reed G T, Ensell G J, Evans A G R, Foote P D, Pritchard A P and Barber D 2003 Bragg Gratings Interrogating System using MEMS and Optical Circuits: Proc. SPIE 4997 Photonics Packaging and Integration III (San Jose, 25 January, 2003) (Bellingham: SPIE) pp 232–41

[19] Keddie D P et al 2004 Bragg Gratings Interrogation System using MEMS and Optical Circuits: Part 2, Component Development: SPIE Photonics West Invited Talk (McEnery Convention Center, San Jose, 24-29 January, 2004)

[20] Kersey A D, Danbridge A and Tveten 1987 Recent Advances in Demodulation/Multiplexing Techniques for Interferometric Fiber Sensors: Proc. SPIE 0734 Fibre Optics '87 ed L R Baker (London, 28 April, 1987) (Bellingham: SPIE) pp 261–9

[21] Xiao-qin N, Ming W, Xu-xing C, Yi-xian G and Hua R 2006 An optical fibre MEMS pressure sensor using dual-wavelength interrogation Meas. Sci. Technol. 17 2401–4

[22] Ge Y, Wang M, Chen X and Rong H, 2008 An optical MEMS pressure sensor based on a phase demodulation method Sensors and Actuators A 143 224–9

[23] Cong-fei W, Guang-long W, Jian-hui C and Yi D 2009 The Signal Interrogation Technology of MEMS Optical Fiber Pressure Sensor: ICIA’09 Int. Conf. Information and Automation (Zhuhai, 22-24 June 2009) pp 1285-8

[24] Yang J, Qiu C, Wang Q L, Wang M H and Yang J Y 2013 Tunable microring filter based on-chip interrogator for wavelength-modulated optical sensor Key Engineering Materials 562–565 265–7

[25] Hill K O and Meltz G 1997 Fiber Bragg grating technology fundamentals and overview J. Lightwave Technology 15 1263–76

[26] Todd M D, Nichols J M, Trickey S T, Seaver M, Nichols C J and Virgin L 2007 Bragg grating-based fibre optic sensors in structural health monitoring Phil. Trans. R. Soc. A 365 317–43

[27] Metje N, Chapman D N, Rogers C D F, Henderson P and Beth M 2006 Optical Fibre Sensors for remote monitoring of tunnel displacements – prototype tests in the laboratory Tunnelling and Underground Space Technology 21 417

[28] Glavind L, Olesen I B, Skipper B F and Kristensen M 2013 Fiber-optical grating sensors for wind turbine blades: a review Optical Engineering 52 030901-10

[29] Hammon T E and Stokes A D 1996 Optical Fibre Bragg Grating Temperature Sensor Measurements in an Electrical Power Transformer using a Temperature Compensated Optical Fibre Bragg Grating as a Reference: 11th Int. Conf. on Optical Fiber Sensors (Sapporo, Japan, 21 May, 1996) (Washington DC: Optical Society of America) pp 566-9

[30] Higgins A J and Hook I K 1995 Optically Powered Isolated Sensors: Proc. Electronic Technology Directions to the Year 2000 (Adelaide, 23-25 May 1995) (Digital library: IEEE Xplore) pp 301-5