INNOVATIVE ASSET MANAGEMENT

Full Paper

PHOTONIC TECHNOLOGIES IN SMART STRUCTURES

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ABSTRACT

The relatively new field of Photonics has resulted from many years of investment in electro-optic technology development across a wide range of applications. These technologies have revolutionised the world of telecommunications by providing orders of magnitude increase in bandwidth, driven by a substantial growth in the use of the Internet.

Photonic technologies have wide ranging implications to the building and construction industry apart from simply 'wiring' a building or structure for communications through the use of optical fibre. This paper presents an overview of new and existing building and construction applications of technologies that have resulted from a substantial worldwide investment in this emerging technology area.

Asset management, OH&S, security, and client comfort are the key drivers for Photonics in complex structures, and this paper will demonstrate the potential to provide high spatial resolution, wide coverage monitoring of a number of important parameters including temperature, strain, environmental factors, and indicators relevant to security. For example, the ability to monitor temperature fluctuations at very high spatial resolution across the walls, ceiling, and floor of a building with fast response (effectively several thousand independent sensors) has implications for fire detection and control, security monitoring, and environmental control of the building as a whole.

Technical details will be presented of fundamentally new photonic devices that have the potential to monitor strain in civil structures such as bridges, tunnels, and dams as well as in complex mechanical structures such as aircraft. The ability to continually monitor extremely high resolution strain in a bridge, for example, when repetitive loadings are experienced, will enable very early indications of failure to be detected. When networked these devices may occupy the same communications backbone that supplies voice, data, and other sensor information to a central control, further reducing their cost.

Keywords: distributed sensing, strain, temperature, fibre bragg grating, optical fibre sensing.

1. INTRODUCTION

The whole-of-life structural integrity of major fixed infrastructure and smaller but more dynamic transport platforms is critical. Issues resulting from the original design together with normal and abnormal wear and tear mean that continuous, realtime monitoring both during construction and normal operation provide significant opportunities to avoid catastrophic failure. Basic design issues have presented significant challenges as the use of lighter materials and novel design approaches have reduced the margin for error. Recent events such as the 'wobble' in the new Millennium Bridge in London are timely illustrations of the challenge.

Since the mid seventies Photonic technologies have promised to change fundamentally the ability to monitor complex structures in realtime, at high spatial resolution, and at low cost. In this period advances in distributed optical fibre sensing have delivered solutions for measuring temperature and other parameters as a tool for industrial process control in specialist applications, but the cost benefit barrier had not been penetrated.

Early attempts to use the unique properties of light, specifically in a fibre based spectroscopic mode, to measure parameters such as temperature (Dakin, 1985, Paton, 1990, Samson 1990) , vibration (Weir, 1991), gas composition (Scott, 1990), strain (Ohba, 1989) and pH (MacCraith 1991), resulted in systems that were relatively expensive and limited in performance. The commercialization of systems based on these technologies was therefore limited and did not lead to the market penetration that was originally predicted.

Recent advances in distributed, quasi distributed, and discrete optical fibre sensor technology have brought the technology very close to the stage when applications such as monitoring infrastructure ranging from large civil structures, for example bridges and dams, to performance monitoring of complex mechanical structures, such as aircraft frames and skin, for strain, temperature and other parameters is now possible.

One particular sensing device based on the Fibre Bragg Grating (FBG) has generated considerable interest with its potential to network a very large number of sensing elements in a strain gauge configuration to enable embedded broad area strain measurement for realtime monitoring. When integrated with other sensor elements these systems result in a powerful monitoring capability (Li, 2003).

The same technology is being applied to a number of other key sensing processes, including; Geophones and hydrophones for hydrocarbon exploration and defence sonar, and multi-element phase sensitive microphones for defence and other applications.

This paper presents an overview of a number of sensing techniques, including this new approach, and considers their application in areas relevant to structural health monitoring .

2. THE OPPORTUNITY

From a structural integrity perspective the high level requirements of a practical sensor system has been identified as:

- Strain and/or temperature measurement
- Physically small – non intrusive
- Environmentally rugged
- Does not introduce electromagnetic interference
- Is not interfered with by other sources of noise
- High spatial resolution
- Low cost per sensor
- Easily networked
- Scaled to a large number of sensors

These performance parameters have been the target for the development of optical fibre based sensor network for measuring strain and temperature. Some of these parameters are more important in certain applications, for example, to build a sensor into a composite structure such as an aerofoil surface or aircraft frame having the sensor extremely small and non intrusive is imperative. In addition, if the structure is experiencing complex forces under transient conditions then high spatial and temporal resolution measurements will be required.

In contrast, instrumenting railway bridges to provide an early indication of failure would require a large number of sensor elements possibly a long distance from the monitor, with high temporal resolution being required in short bursts.

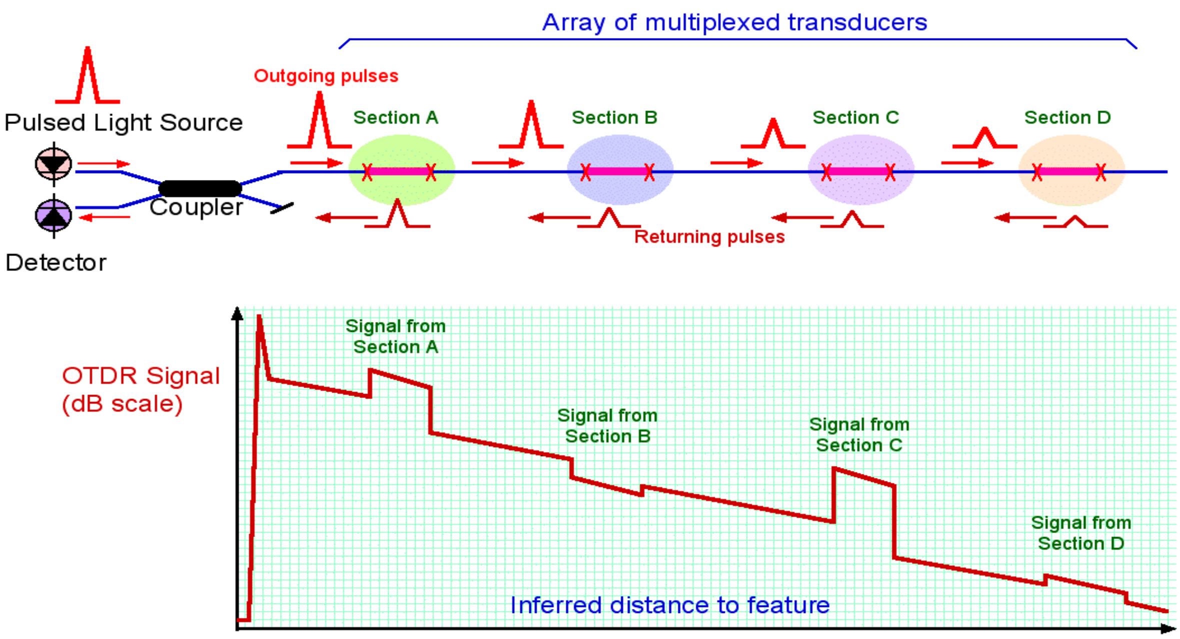
In addition, sensors meeting the above targets provide an opportunity to contribute significantly to the longstanding promise of the ‘smart’ building. Because the path of a sensor array is defined by the optical fibre itself, the fibre when built into the walls, ceilings, and floor of a building encapsulates the area in sensors. If these are, for example, temperature sensors the system will produce detailed knowledge of the distribution of temperature around periphery of the area – and this can be used to:

> control airconditioning at individual exit ducts so an area can be maintained at a uniform temperature irrespective of the heat loading at different parts of the area (eg west facing windows),
>
> control alarms and sprinkler systems for fire prevention, having the benefit that detecting more localized small sources of heat will provide an earlier indication of a source of fire,
>
> enhance security through the detection of radiant heat changes both temporal and spatial, which might be associated the passage of an intruder.

The ability to build the fibre into the skin of the interior of a space and reduce its thermal response time will be a determining factor in the uptake of this technology for this application.

3. THE TECHNOLOGY

Conventional optical fibre sensors for temperature and strain use a specific scattering feature of an optical fibre where this feature changes with a change in the measured parameter. The feature might be a scattering property of the silica core of the fibre, for example Raman or Brillouin scattering which are directly effected by temperature and stress respectively. Figure 1 shows the distributed nature of this natural scattering and a configuration based on Optical Time Domain Reflectometry (OTDR) for interrogating the scattering magnitude – operating on the same principal as radar but at optical frequencies and confined to the fibre.



Optical Time Domain Reflectometry (OTDR) – Distributed Measurement.

A pulse of light is injected into a fibre where it travels along the fibre and is scattered back to a detector, via a coupler, from the entire length of the fibre. The scattering from each section is separated in time at the detector so the scattering at each section (A, B, …X) acts as a discrete measurement. This is the basis of current commercial distributed temperature measurement devices.

The effectiveness of the sensor section of the fibre can be increased by modifying the core of the fibre to make it more sensitive to the parameter being measured. A relatively simple fibre based temperature measurement technique based on the introduction of a dopant to the core of the fibre has been commercially exploited. It is based on fluorescence lifetime decay in fibre that has been doped with a fluorescent material, such as neodymium.

Figure 2 illustrates the approach. A short pulse of light is injected into a fibre where it is absorbed by the fluorescent dopant which in turn fluoreses with a decay time directly dependent on the temperature of the fibre. The technique provides a single point measurement and cannot be easily converted to a linear array using the OTDR approach because of interference with the fluorescence decay in the time domain.

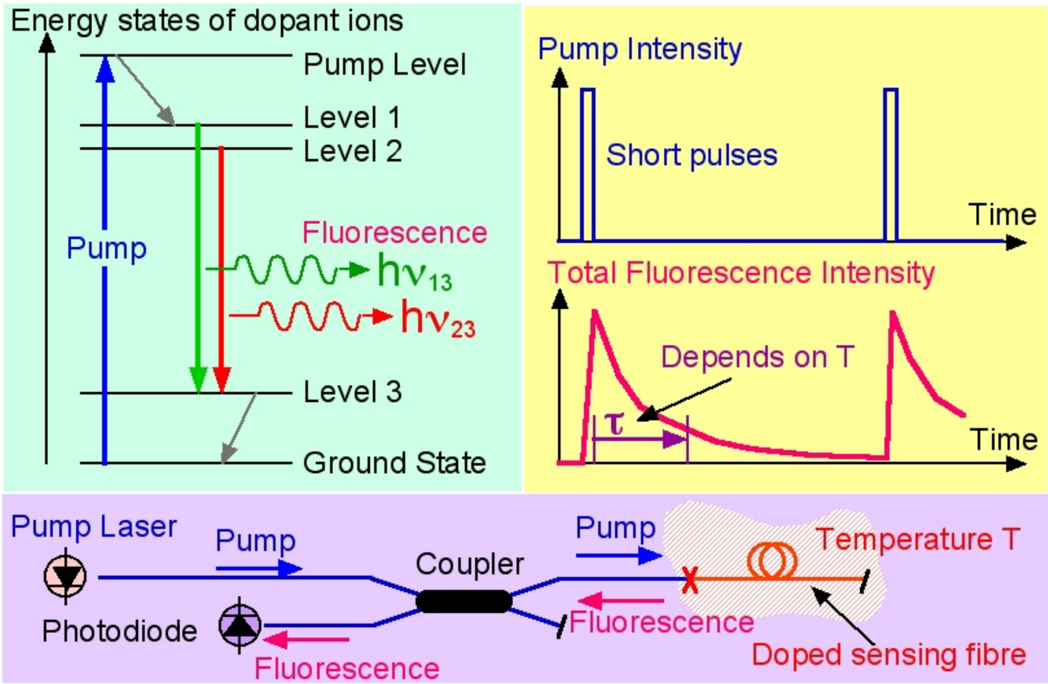


Figure 2.
Fluoresence Decay Temperature Measurement.

3.1 FIBRE BRAGG GRATINGS

A different type of sensor scattering section that can be introduced to the core of an optical fibre to enhance its detection properties is a Fibre Bragg Grating. These are analogous to a conventional optical diffraction grating where a series of physical discontinuities (lines) spectrally modify light by diffraction and have the effect of an optical filter.

The diffraction grating is formed in the core of a relatively standard optical fibre using a ‘printing’ process where the fibre is exposed to UV light in a way that leads to regions of high and low refractive index within the core. This periodic high and low refractive index forms a diffraction grating, or filter, that operates only on the light within the fibre. The printing process is extremely flexible and gratings with very complex spectral characteristics can be manufactured in a reproducible manner in large quantities.

These are the devices used in telecommunications systems to multiplex multiple channels of information in a fibre through a process known as Dense Wavelength Division Multiplexing (DWDM). Figure 3 is a schematic diagram of an FBG within a fibre and a simple example of the filter characteristics that can be obtained. The filter operates on the incident broadband light entering from the left producing a backscattered signal exiting to the left and a residual transmitted signal exiting to the right.

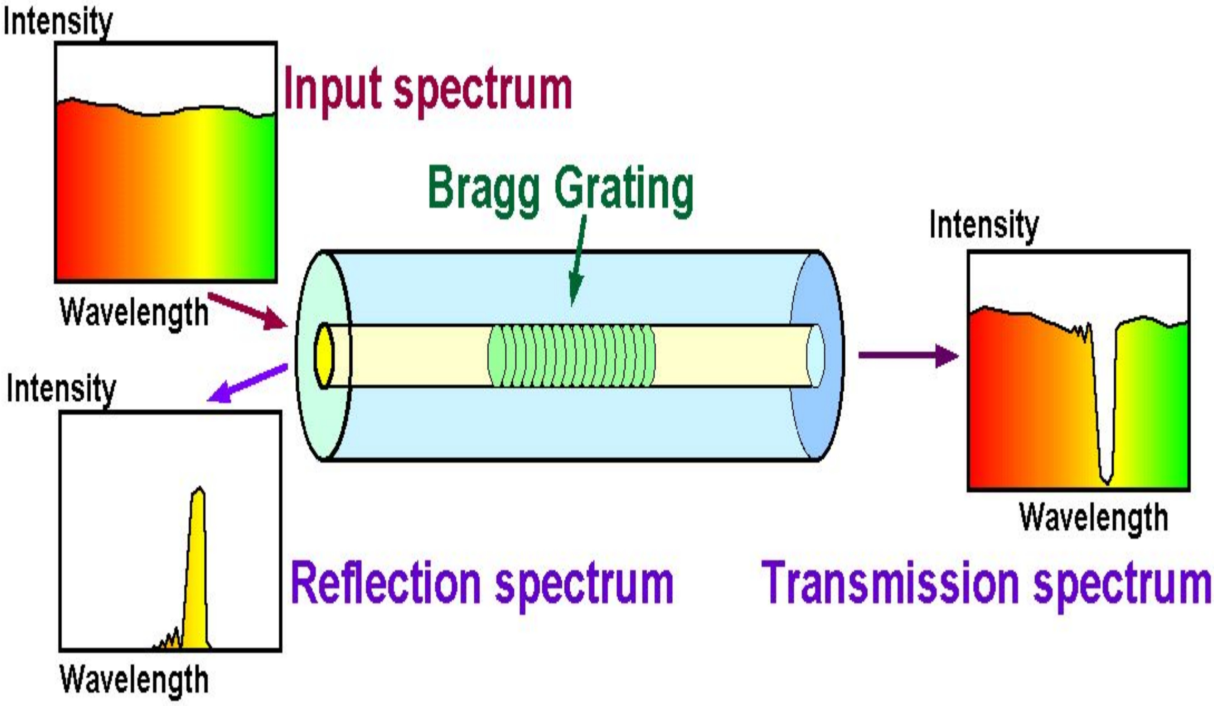


Figure 3. Fibre Bragg Grating

The FBG can be ‘printed’ into the fibre anywhere along its length and in large numbers. In a simple form each FBG becomes a point of measurement. For strain measurement it is easy to see that if the fibre is stretched the period of the grating changes and the spectral characteristics of the backscattered or transmitted light occurs. A simple spectrometer is used to interrogate the strain signal from the spectrum and if each FBG is slightly different many sensors can be placed in the same fibre interrogated simultaneously.

Figure 4. shows a networked array of point sensors which may be configured for strain and/or temperature measurement. Several hundred sensors may be placed in a single fibre and the sensing elements can be placed in any spatial configuration required. Many of these single fibre arrays can then be multiplexed to proved thousands of points of measurement with a single interrogation system mounted many 10’s of kilometers away

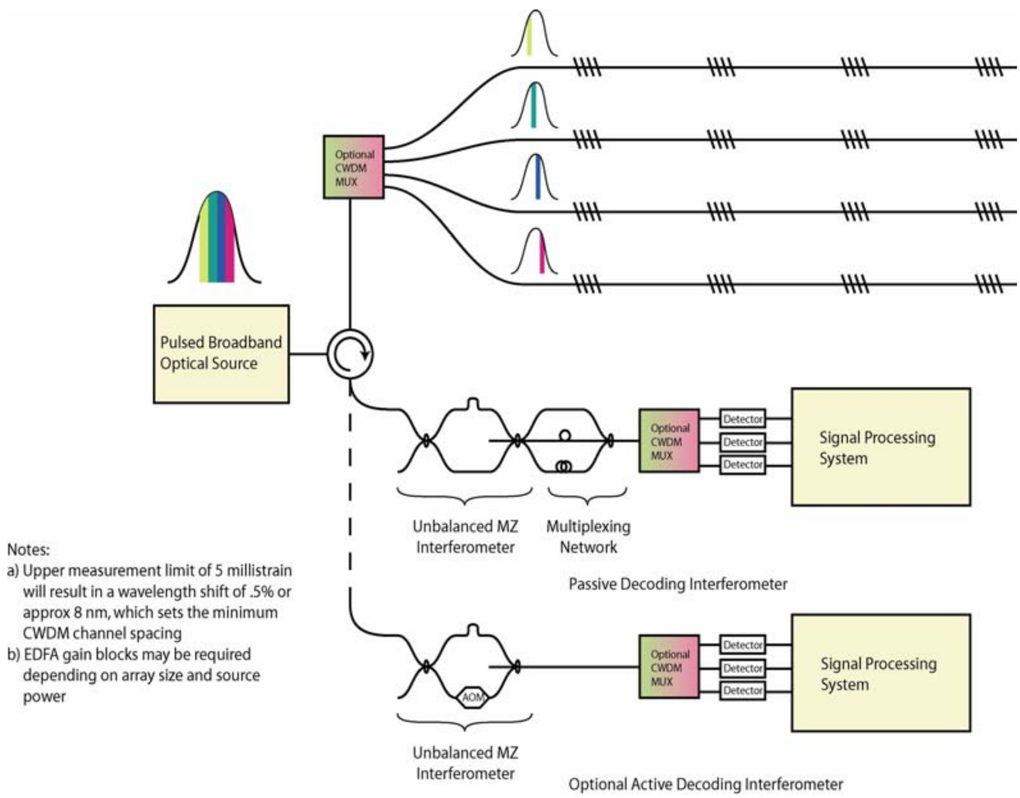


Figure 4. Point Array of Sensors

This configuration is suitable for discrete multiple point strain sensing covering large areas, a long distance from the observer. Applications include multiple (up to several hundred) point strain measurement in concrete and steel bridges, dams, tunnels, complex structures such as powers stations and processing plant, and anywhere a large number of discrete points are required to be monitored. The basic version measures one axis of strain at each point, a more advanced configuration measures multiple axes at each point.

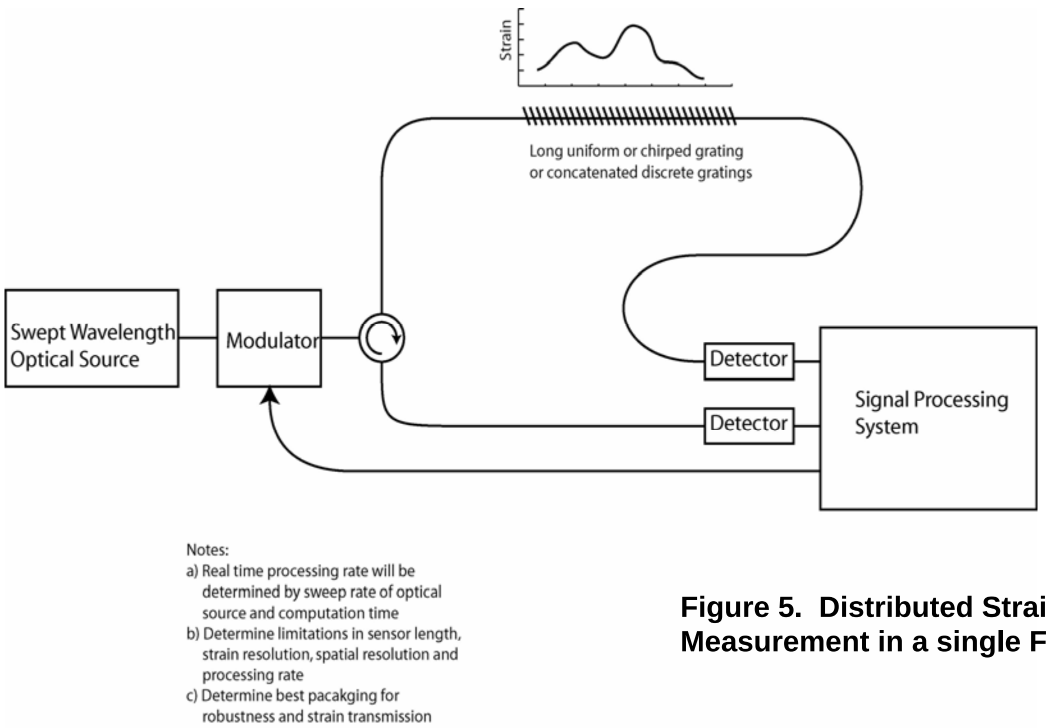


Figure 5. Distributed Strain Measurement in a single FBG

4. DISTRIBITED STRAIN MEASUREMENT

If a long FBG (up to 10 centimeters) is printed into a fibre and the FBG is designed to have certain spectral characteristics then it is possible to measure strain (or temperature) distributed along the length of the FBG. Due to the flexible process for printing the FBG into the fibre a grating with a gradual change in 'line' spacing (chirp) can be generated, this in effect becomes an array of slightly different gratings.

In Figure 5. an FBG is shown in an interrogation configuration that enables strain as a function of position along the FBG to be measured by spectrally separating different regions within the grating. The spatial resolution might be just a few millimeters so the measurement is effectively hundreds of discrete points spaced at millimeter intervals over a 10 centimeter length. The fibre may be wound or laid out in a way that produces an area of very precise high spatial resolution strain/temperature measurement.

The above discussion focuses on single fibres. If multiple fibres or a single fibre with multiple cores is used to carry a sensitive scattering region it is possible to measure the parameter (such as stress) in directions other than longitudinally within the fibre. If the multi core sensor is a temperature sensor and the cores are not highly thermally coupled it is possible to measure thermal fluxes by the temperature differences across the fibre. The application of these multi core fibres are numerous.

5. BEYOND THE FIBRE BRAGG GRATING

A family of fibres called 'Holey' fibres is beginning to be developed for a range of applications including telecommunications and sensing. These fibres do not rely on a different material to change the refractive index of the fibre to define the core, but use an array of holes running along the length of the fibre to change the effective refractive index the light will 'see', and hence guide the light.

Figure 6 are micrograph of such a fibre which can be made from silica or polymer.

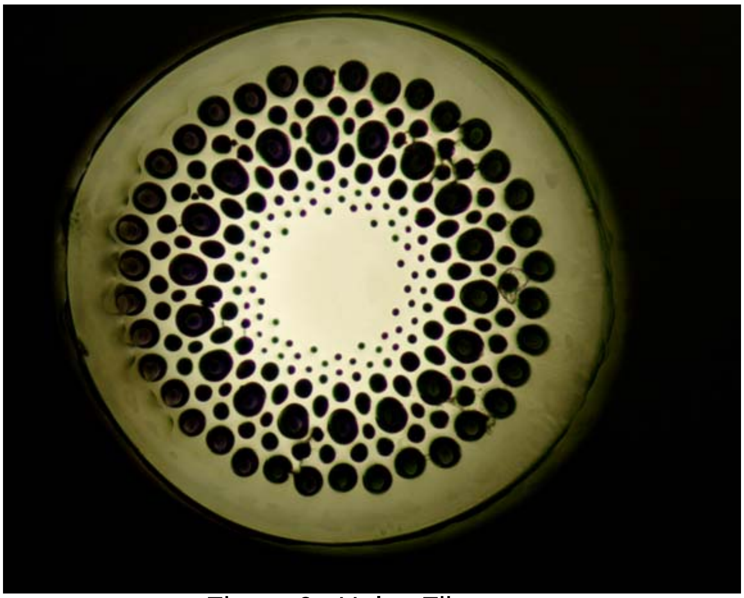


Figure 6. Holey Fibre

The high index core is the section in the center with no holes and the low index cladding has the holes. Apart from the possibility of printing FBG's into the core of this fibre and achieving the benefits outlined above for conventional fibres, its intrinsic physical characteristics (particularly in polymer) make it suitable for distributed monitoring of force, so applications in security and inertial systems are possible. Other applications being considered include the introduction of gases into the holes where the light will interact with the gas in a well defined region enabling spectral characterization of the gas.

6. CONCLUSION

Recent advances in optical fibre technology are creating opportunities for sensor arrays in novel high performance low cost configurations. These sensors are making possible the monitoring of a wide range of complex structures, both during construction and under normal operation, in a way not considered possible before now.

The Australian Photonics Cooperative Research Centre is a leader in the field of novel fibre component and systems R&D and is pursuing collaborations with industry and other groups which will help bring the results of this research to commercial reality. A consortium is being developed which will, initially, focus on construction and aerospace applications.

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