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Graham Wild
Edith Cowan University

Gary Allwood
Edith Cowan University

Steven Hinckley
Edith Cowan University

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Distributed Sensing, Communications, and Power in Optical Fibre Smart Sensor Networks for Structural Health Monitoring

Graham Wild¹, Gary Allwood², Steven Hinckley³

*Optical Research Laboratory, Centre for Communications Engineering Research,
School of Engineering, Edith Cowan University
270 Joondalup Drive, Joondalup WA 6027, Australia*

¹ G.Wild@ecu.edu.au

² G.Allwood@ecu.edu.au

³ S.Hinckley@ecu.edu.au

Abstract— With distributed optical fibre sensors, a single source, a single detector, and a single fibre can be used for up to 1000 fibre Bragg grating sensors. However, this multiplexing architecture is not robust. Damage to any of these individual components can render the entire sensing system useless. To achieve a robust structural health monitoring system, this type of multiplexing cannot be utilised. To overcome the lack of robustness associated with multiplexing optical fibre sensors together, intelligence along with sensors needs to be distributed around a structure. Distributed Optical Fibre Smarts Sensing (DOFSS) represents a sensing architecture for the structural health monitoring of robust aerospace vehicles. The distribution of intelligence around the structure means that communications and power for the network are a significant consideration. Since optical fibre will be utilised for the sensing, then these “wired” links, can easily be utilised for power. The optical fibre links could also be utilised for the distribution of power around the sensor network. In this work, we investigate the distribution of sensing, communications, and power for DOFSS.

I. INTRODUCTION

As spectral transduction elements, the primary advantage of Fibre Bragg Gratings (FBGs) is seen as their ease of multiplexing. As Optical Fibre Sensors (OFSs), FBGs have several other properties that make them of interest to sensing areas, especially Structural Health Monitoring (SHM) [1]. The most significant of these advantages include reduced size and weight, immunity to electromagnetic interference, and most significantly, the versatility of FBGs to detect different measurands. For SHM, a FBG system can be used to detect Acoustic Emissions (AEs), actively generated Acousto-Ultrasonic (AU) signals, dynamic strain (e.g. vibration), static strain (e.g. load monitoring), and corrosion, as well as a variety of other measurands.

As with other OFSs, FBGs have found a niche in applications utilizing multiplexing, such as distributed sensing for large scale structures, including bridges and other civil structures. A number of multiplexing architectures can be applied to FBG sensing, including Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM) [2]. However, multiplexed OFSs, with a single fibre, a single source, a single detector, and a single processor, have an

inherent flaw, a lack of redundancy. If damage occurs to the structure, resulting in damage to any of the four elements of the system, then potentially the system can become inoperative. Optical Fibre Smart Sensors (OFSSs) represent a robust technology with inbuilt redundancies for both sensors and intelligence. For example, this goes towards achieving NASA’s goal of robust or ageless aerospace vehicles, as outlined in the Airframe Structural Integrity and Airframe Airworthiness Programs [3], Ageless Systems. As with other smart sensors, OFSSs utilise local processing power to add intelligence. The use of a local processor then requires an interface to the OFSSs monitored by the processor. To realise OFSSs, a Smart Transducer Interface Module (STIM) was developed [4].

To be effective in SHM, a large number of OFSSs need to be distributed around a structure, that is, Distributed Optical Fibre Smart Sensors (DOFSSs). The use of DOFSSs will enable a smart sensor network to be configured using a large number of STIMs. This will enable a robust SHM system to be realised utilising OFSSs. The use of optical fibres in a network suggests that the system is “wired”, and the issue of network communications and power distribution then needs to be addressed. Since optical fibres containing sensing elements are required, the use of a fibre optic link between the STIMs means that not only can sensors be shared between processors, increasing redundancy; the links could be used for optical communication and power transmission. That is, DOFSSs could be used to form an all optical fibre sensor network, linking nodes together for the distribution of sensing, power, and communication, simultaneously. In this work, we demonstrate the multiplexing of optical sensing, communications and power over a single fibre optic link. In addition to this, two STIMs were connected together, via an optical fibre communications link, with one STIM responsible for sensing, and the second STIM responsible for reporting a fault.

Hence, the goal of this research is to develop a structural health monitoring system based on a DOFSS, where data communications, sensing and power transmission are all achieved using a robust all photonic network.

II. THEORY

A. Fibre Bragg Grating Sensor

A FBG [5] is a spectrally reflective component that uses the principle of Fresnel reflection. The grating is made up of alternating regions of high and low refractive indices. The periodic grating acts as a filter, reflecting a narrow wavelength range, centred about a peak wavelength. This wavelength, known as the Bragg wavelength (λ_B), is given by

$$\lambda_B = 2n\Lambda, \quad (1)$$

where n is the average refractive index of the grating and Λ is the grating period.

Any measurand that has the ability to affect either the refractive index or the grating period can be measured using a FBG as a sensor. Specifically, a FBG is sensitive to strain and temperature. The relative change in the Bragg wavelength ($\Delta\lambda_B$) as a function of the applied strain (ϵ) can then be expressed as,

$$\Delta\lambda_B = \lambda_B \epsilon \left(1 - \frac{n^2}{2} [p_{12} - \nu(p_{12} + p_{11})] \right), \quad (2)$$

where ν is Poisons' ratio, p_{12} and p_{11} are the strain optic coefficients.

Equation (2) means that the measurand is encoded onto the wavelength shift of the FBGs. The primary advantage of the absolute nature of wavelength encoding is immunity to optical power fluctuations. However, spectral decoding methods, which are typically slow, cannot be used for very high frequency signals, such as ultrasound. FBGs can also be used as intensimetric sensors, where the sensor signal is recovered via either power detection, or edge filter detection [6]. Power detection was the first method implemented for FBG sensors to detect high frequency acoustic signals [7]. Fig. 1 shows the reflectivity as a function of wavelength for a typical FBG. Centred about λ_0 , there is a linear region, $\delta\lambda$, between reflectivities of approximately 20 and 80 percent. This linear "edge" of the FBG is used as an optical filter. A narrowband laser source centred about λ_0 is then intensity modulated by the strain induced shift in the wavelength. That is, the reflected optical power is varied as the linear edge of the FBG is shifted in the spectrum. The detection of the signal is then achieved using a simple photoreceiver. The STIM was designed to be directly compatible with edge filter detection, or power detection based intensimetric FBG sensor. Specifically, the STIM was designed for use with a Transmit Reflect Detection System (TRDS) [8], where two photoreceivers and a high speed differential amplifier can be used to monitor dynamic strain signals up to 1 MHz (limited only by the response of the FBG).

B. Photovoltaic Power

A Photovoltaic Power Converter (PPC) is basically a photodiode operating in photovoltaic mode. Hence, we are

concerned with the behaviour of the device in the fourth quadrant of the I-V curve, where the device actually generates power. The maximum power produced is the point on the I-V curve where the current multiplied by the voltage (the power) is at a maximum. This is given by setting the derivative of the power with respect to the voltage equal to zero. Fig. 2 shows the typical I-V and P-V curves of a photovoltaic cell.

Fig. 1. The relevant parameters for power detection with a FBG shown on a typical reflectivity plot.

Fig. 2. Typical I-V and P-V curves of a photovoltaic cell under illumination.

The parameters that define the performance of a photovoltaic cell are the short circuit current (I_{sc}), the open-circuit voltage (V_{oc}), and the fill factor (FF). The short circuit current occurs when the load, and therefore the voltage, equals zero and is equivalent to the photocurrent. The open circuit voltage occurs when the resistive load is considered infinite producing no net current. The fill factor is the ratio of the peak output electrical power to the product of I_{sc} and V_{oc} .

C. Optical Fibre Communications

Attenuation in optical fibres is an important factor as it ultimately determines the cost of an optical network. If the attenuation is significant then a large number of repeaters are required, resulting in a more expensive network. Attenuation in a silica fibre is a result of both scattering and absorption of the optical signal. Attenuation in an optical fibre can be quantified using,

$$\beta = 10 \log \left(\frac{P}{P_0} \right), \quad (3)$$

where P and P_0 are the output power and input power, respectively. Equation (3) also gives the loss (in decibels) of power. This could be based on the addition of various photonic components, such as couplers and WDM filters.

III. EXPERIMENTS

A. Smart Transducer Interface Module

The Smart Transducer Interface Module (STIM) has previously been reported [4]. It is made up of a TI Digital Signal Processor (DSP), on an eZdsp general purpose evaluation board. The DSP has an onboard 16 channel Analogue to Digital Converter (ADC), capable of sampling the high speed signals for either acoustic sensing, or for communications. The DSP also has available a large number of general purpose I/O.

B. Sensing

The FBG sensor was used as a dynamic strain sensor. The FBG sensor used a transmission based power detection method [9] to convert the wavelength shift of the FBG into an intensity signal for the receiver. A tunable laser (Ando AQ 8201-13B) was used as the source for the power detection, which was directed via the sensing FBG (Broptics GF-1C-1554.13-RX2) to the photoreceiver (Fujitsu FRM3Z231KT). The signal for the receiver was then inverted using an inverting amplifier with a gain of 1. This was then connected to the ADC for sampling. The first STIM was then used to switch the communications laser, connected to an I/O pin, via a simple transistor switch. The communications signal was then directed to a second receiver which made use of a comparator to convert the communications signal into a TTL compatible digital signal. Fig. 3 shows the configuration of the STIMs used in the sensing experiments.

C. Power

First the optical power of the 980nm Laser Diode (LD), SDLO-2433-090, was calibrated using the manufacturers supplied data. From here, a measurement was taken using an optical power meter. The LD was biased using an injection current of 14.5mA, from a constant current DC power supply (Goodwill GPS-3030). The voltage of the power supply was set to 1.775 V, the turn on value of the LD. From here, the injection current could then be directly varied with the current adjust dials. The injection current was monitored using an ammeter (Goldstar DM-331).

For the electrical power measurements, the silicon photodiode (Centronic OSD5-5T) was connected in series with an ammeter (Goldstar DM-331) and a decade resistance box (used as the load), and in parallel with a voltmeter (Goldstar DM-331). The resistance was varied logarithmically to generated data for the I-V and P-V curves. To determine the peak power when varying the input optical power, the resistance was varied manually to track the peak power point.

Fig. 3. Experimental setup for the I-V and P-V characterisation of the silicon photodiode.

Fig. 4 shows the experimental setup used to obtain the I-V and P-V characteristics. When measuring the optical power, the optical power meter was used in place of the photodiode.

Fig. 4. Experimental setup for the I-V and P-V characterisation of the silicon photodiode.

D. Multiplexing

To test the use of a single fibre optic link for the simultaneous transmission of optical signals for power, sensing, and communications, a test was performed prior to using the STIM. The experimental setup for this multiplexing experiment is shown in Fig. 5. The communications signal was generated by On-Off Keying (OOK) a 1552nm laser diode (Mitsubishi LDFU-6275LD-F1) via a simple transistor switch controlled by a function generator (used in place of the digital I/O of the STIM). This was combined with the 1554.13nm tunable laser signal for the sensing via a simple 3dB coupler (Wave Optics 12938). Ideally, a WDM filter should be used to reduce losses. Next the two 1550nm signals were multiplexed with the 980nm laser diode signal (powered by the constant current source as before) via a WDM filter (DP95000102A2222). The FBG sensor was then connected after the WDM filter such that all three optical signals passed through the FBG. After the FBG, the 980nm signal was dropped using a second WDM filter. This was then directed to the silicon photodiode for power generation. The two 1550nm signals were kept together and detected with the same photoreceiver. The combined signals could then be TDM (due to the use of OOK), or they could be filtered in the electrical domain, since the optical communications signals could easily be at frequency greater than 1 MHz, while the frequency of the sensing signals would be less than 1 MHz. The same receiver and inverting amplifier from the sensing experiment was used for the multiplexing experiments. A DSO (Agilent 54600A) was used in place of the ADC of the STIM to display the information.

Fig. 5. Experimental setup for the multiplexing of the power, communications and sensing signals over a single optical fibre link.

IV. RESULTS

A. Power-over-Fibre

Fig. 6 shows the IV and PV curves for the simple silicon photodiode, illuminated by the 980nm laser diode. The injection current was set to 120mA. The calibration curve to convert the injection current to output optical power (shown in Fig. 7) gives an optical power of 62mW. Fig. 8 shows the transfer function, to convert the injection current (directly proportional to the optical power, from Fig. 7), to output electrical power.

Fig. 6. I-V and P-V curves of the silicon photodiode with 62mW input power.

Fig. 7. Calibration curve to convert the injection current to output optical power for the 980nm laser diode.

Fig. 8. The transfer function converting the injection current of the 980nm laser diode into output electrical power of the silicon photodiode.

B. Multiplexing

Fig. 9 shows the three multiplexed optical signals. This includes the WDM 980nm signal for power-over-fibre, and the TDM 1550nm signals, specifically the 1552nm optical communications signal, and the 1554.13nm optical fibre sensing signal.

Fig. 9. The three multiplexed signals. Top, WDM 980nm power signal, and bottom, the TDM 1550nm communications and sensing signals.

V. DISCUSSION

A. Power-over-Fibre

Fig. 6 shows a low fill factor, with an approximate short circuit current of 12mA, the theoretical maximum power is then, 7.2mW. With a measured value of 2.6mW, the fill factor is then 36%. Compared with the 62mW of incident optical power, this gives an efficiency of 4%, or a power gain of -13.8 dB using (3). Note that this power attenuation is due primarily to the inefficiency of the photovoltaic cell, with a small contribution from the losses in the optical fiber.

The most significant result of the power-over-fibre experiments is the transfer function. The output electrical power appears to be related to the injection current via a logarithmic relationship. That is, as the input optical power is increased, the output electrical power increases at a lower rate. The result of this, combined with a minimum injection current (given as 9.5mA in Fig. 7), is that there is a peak efficiency.

This occurs with an injection current of approximately 20mA, or an optical power of 6mW. This gives an efficiency of 10.8%, considerably higher than the 4% with from Fig. 6. If the laser diode was operated at its maximum optical power of 120mW, then a single PPC would generate approximately 3.2mW of electrical power. However, if this was split in the optical domain, into 20 6mW signals, and converted into electrical power, this would generate 12.96mW of electrical power. That is an increase by a factor of 4. This splitting could be done with an array of PPCs using a single optical fibre, or with optical splitters to separate PPCs via multiple optical fibres.

B. Multiplexing

The results of the multiplexing, shown in Fig. 9, suggest that TDM can easily be used to combine multiple 1550nm signals. This includes the sensing and communications signals. The impact signal can be easily seen imposed on the OOK digital communications signal. Due to the frequency difference between quasi-static sensing signals, dynamic sensing signals, and communications signals, these three components could also be split by filtering in the electrical domain. Alternatively, the signals could be combined and split using Dense WDM (DWDM) filters. This would require the use of additional receivers, which would also require additional power. The WDM of the power signal with the 1550nm signals also suggests that an all-optical network is viable for the distribution of power and information optically.

C. Future Work

The final stage of the DOFSS work on sensing is the WDM of three FBGs. This is required for both static strain and acoustic sensing. For the acoustic sensing, the multiplexing of three FBGs will enable the source of acoustic emissions to be triangulated. This is important for the localisation of damage in SHM. For the static strain sensing, the multiplexing of three FBGs will enable all of the coefficients of the in-plane strain to be determined, by using the three FBGs as a strain gauge rosette. The current STIM is capable of sampling the WDM signals from the three FBGs, with the use of multiple photoreceivers, by TDM. Fig. 10 shows the final stage of the DOFSS work, with the fully multiplexed link, connecting two STIMs, for sensing, communications, and power.

Fig. 10. Final configuration of DOFSS STIM to STIM connection.

With the successful implementation of WDM for three FBGs for a single STIM, four lots of multiplexed sensors will be cloned. These will be used to monitor in four separate

directions. This will require the addition of 3 more STIMs (in addition to the two used in this work). This will give a DOFSS network test bed, which is the final goal of this project.

Coarse WDM (CWDM) could also be used to combine the sensing and communications signals at separate wavelengths. The advantage of this is that the algorithm used for the TDM of the sensing and communications signal would not be required. A power budget would need to look at the advantages and disadvantages associated with TDM and WDM. WDM would result in simpler processing, but requires additional sources and receivers. Alternatively, TDM is more processor intensive; however, it requires fewer optoelectronic components.

Although the efficiency of the PPC reported here is only 10.8% efficient, it is important to note that this is with a silicon photodiode that is not intended for use as a photovoltaic device, or specifically for 980nm. Simulations of a PPC using a simple homojunction structure suggest that when optimised for 980nm, an efficiency of 43% could be achieved [10]. This is comparable to the 45% efficiency of a complex pearl cell previously reported [11]. However, the use of a homojunction would make an array of PPCs easier to fabricate as a system on a chip. Future work will involve the fabrication of a silicon photovoltaic micro-cell optimised for use as a PPC for operation at 980nm.

Future work on the PPC will also confirm the division of the optical power in the optical domain, using multiple silicon photodiodes. This requires the acquisition of a 3dB coupler at 980nm. A similar method will be used, however, the optical power from the 980nm laser will be split between the two silicon photodiodes to confirm that it is more efficient to utilise multiple PPCs.

VI. CONCLUSION

In conclusion, we have demonstrated the simultaneous transmission of optical signals for power, communications, and sensing, over a fibre optic link for an optical fibre sensor network. The combination of optical signals for sensing and communications was achieved with time division multiplexing at 1550nm, and the addition of an optical signal for power was achieved with the use of wavelength division multiplexing of 980nm. The sensing and communications signals could easily be decoded in the electrical domain, while the power signal was removed in the optical domain.

The work on distributed power shows a peak power conversion efficiency, measured at 10.8%. This peak efficiency occurred at an optical power of 6mW. With the development of a silicon photodiode specifically for photovoltaic power conversion at 980nm, this efficiency could be significantly improved.

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