Secondary student research projects in engineering: optical fibre Bragg grating sensor applications

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***Abstract**: In this paper, we present a study of secondary student research projects on fibre Bragg grating (FBG) based optical fibre sensors. Our study has shown that simple experimental procedures can be developed and implemented by students with minimal prior knowledge. In these experiments, students gain a significant understanding of FBG properties and performance, as well as an understanding of research, data analysis and communications skills required by researchers. Student satisfaction and enjoyment with the programme is very high, based on feedback received. These research-based projects would be ideal for implementation into undergraduate engineering learning programmes.*

Introduction

Evidence suggests that research-focussed projects form one of the most effective learning methods in undergraduate engineering (e.g. Mills & Treagust, 2003; Bachrak, et. al., 2006; Harsanyi & Lepsenyi, 2000). Also, one of the key factors in developing an understanding and interest of engineering in secondary students is real-world activity-based learning (Dawes & Rasmussen, 2007). These methods are important for engendering interest among students for developments in engineering, and to explore the possibility of future careers in engineering. An additional problem among tertiary institutions in Australia is the reduced articulation of domestic undergraduates into postgraduate research programmes (Le & Tam, 2010).

In general, a lack of engagement of secondary students has “failed to foster and develop innate curiosity and interest” (Hollow, 2000) in science and engineering. This has led to a reduction in interest in pursuing careers in these fields through further study at the tertiary level in Australia (Dawes & Rasmussen, 2007) and overseas (UNESCO, 2010). To counter this trend, a number of different studies have been performed, with varying degrees of success. These studies include examining targeted outreach programmes (Carnegie, et. al., 2011), educational summer camps (Gregg & Chen, 2005), team-based engineering project activity (Villanueva et. al., 2011), and the introduction of engineering teaching programmes into secondary education curricula (Arsenault et. al. 2005).

The implementation of research-based projects for secondary students is increasing (Hollow, 2000; Lam & Lim, 2001). Research-based activities for senior undergraduate and postgraduate students have been implemented and have demonstrated a significant improvement in student motivation and the development of research skills (e.g. Bachnak et. al., 2006; Celebi & Qaraqe, 2011; Kane, 2009). The potential to articulate these programmes into junior undergraduate engineering teaching programmes is significant. The same is also true for undergraduate project students. Here a similar exposure to subprojects within a research group gives the potential to articulate these students into postgraduate engineering programmes. In the United States, the National Science Foundation (NSF) even encourages this process, providing grants to teaching institutes that complete research projects with undergraduate students through the Research Experiences for Undergraduates programme (NSF, 2011).

Student Project Background and Description

For a number of years, Edith Cowan University (ECU) staff have supervised senior secondary student research projects. The projects are performed by senior secondary students, that is, students usually enrolled in Year 12 high school under the WA TEE Curriculum programme, but may also include some Year 10 and 11 students. This programme includes students participating in the CSIRO Student Research Scheme. This paper summarises the performance and experiences of four students engaged in activities on FBG-based sensor experiments in 2007 and 2008. Students perform a short term (6-10 week) research project under the supervision of an academic staff member, with the assistance of honours and postgraduate research students. This affords an opportunity for secondary students to get a taste of research within a tertiary institution, and also for research students to develop their engagement and supervisory skills. The projects emphasise the importance of good experimental technique, and the correct methods of data analysis and interpretation. At the completion of the project, the student researchers prepare a poster and give a poster presentation to the research community, which includes their peers, undergraduate, Honours and postgraduate students, and staff.

The objectives of this programme were to (i) determine the suitability of this type of learning activity for secondary students with a limited background in the topic to be investigated, (ii) develop a level of engagement with the students to foster and develop innate curiosity and interest in science and engineering, and (iii) generate a potential path for student enrolment in tertiary study in science and engineering. Students completing the TEE Secondary program in Western Australia receive limited exposure to optical fibres, as they are only required "to understand the impact of inventions such as internal combustion engines, electronic components and optical fibres on energy use" (Curriculum Council, WA, 2005).

Student work was evaluated by the academic staff for quality in terms of laboratory notebook recordkeeping (an essential skill for any future graduate), experimental skills, ability to analyse results and draw simple conclusions, ability to discuss their results, and communication skills in preparing and delivering a poster presentation. The assessment criteria were identical to those applied to second year undergraduate engineering and physics students at ECU. At the completion of the programme, each student was asked to provide qualitative feedback on a survey of their perceptions of the exercise.

Optical fibres have significant potential for communications and sensing applications (Othonos & Kalli, 1999). One of the major areas of research in the School of Engineering at ECU is in fibre Bragg grating (FBG) based optical sensors, especially for application to structural health monitoring (Wild & Hinckley, 2007). In this paper, we present a collection of results from a number of student-oriented research projects performed within the Photonics Research Laboratory of the Centre for Communications Engineering Research (CCER) at ECU. In the examples presented in this paper, students examined and characterised the performance of FBG optical fibres, and applied these sensors to the problem of measuring a number of physical parameters. In particular, these experiments emphasise the importance of this technology in current and future engineering applications, and are suitable for incorporation into undergraduate teaching, as research-informed teaching activities with a significant student participant focus. Our investigation has found that there have been no reported studies of this type of programme on FBG sensors, either at the secondary or undergraduate level, although some senior undergraduate and graduate optoelectronic sensor based programmes have been documented (Vengarkar, Murphy & Claus, 1992; Sherry & Lord, 1997). For these later programmes, participants have, in general, a significant background in the concepts of optics and optical fibres.

Background FBG Theory

A fibre Bragg grating (FBG) is a short section of an optical fibre that is manufactured to reflect a particular wavelength of light and to transmit all others. This is achieved by having a repetitive variation to the refractive index in the core of the optical fibre, as shown in Figure 1. Due to the fact that at a change in refractive index some light is reflected, the wavelength of the light that corresponds to the Bragg wavelength will be reflected, while all others will be transmitted. Hence, the FBG acts as a wavelength specific dielectric mirror. The Bragg wavelength (λ_B) is given as (Hill, 1978),

$$\lambda_B = 2n\Lambda, \tag{1}$$

where n is the average refractive index (average of n_2 and n_3 in Figure 1), and Λ is the grating period. Hence, any phenomena that affect the refractive index or the grating period will result in a change in the Bragg wavelength. This allows FBGs to be used in sensing applications. For example, if there is a change in the length of the FBG due to strain, the spacing between the dielectric mirrors changes, so the wavelength that the FBG reflects changes. In this instance, the change in length will decrease the optical density of the fibre, which would decrease the refractive index. The change in Bragg wavelength due to the effects of strain and temperature is (Archambault, Reekie & Russell, 1993),

$$\Delta\lambda/\lambda = C_S\varepsilon + C_T\Delta T, \tag{2}$$

where λ is the initial Bragg wavelength, $\Delta\lambda$ is the change in wavelength, C_S is the strain coefficient, ε is the strain, C_T is the temperature coefficient, and ΔT is the change in temperature. According to equation (2), changes in temperature will also affect the Bragg wavelength. Strain effects in FBGs can also relate axial and transverse effects. If a downward force (pressure) on a horizontal FBG compresses the fibre, reducing the fibre diameter, then this will result in an extension in length; the transverse strain (ε_x) is related to the axial strain (ε_y) by Poisson's ratio (ν) as, $\varepsilon_x = -\nu\varepsilon_y$.

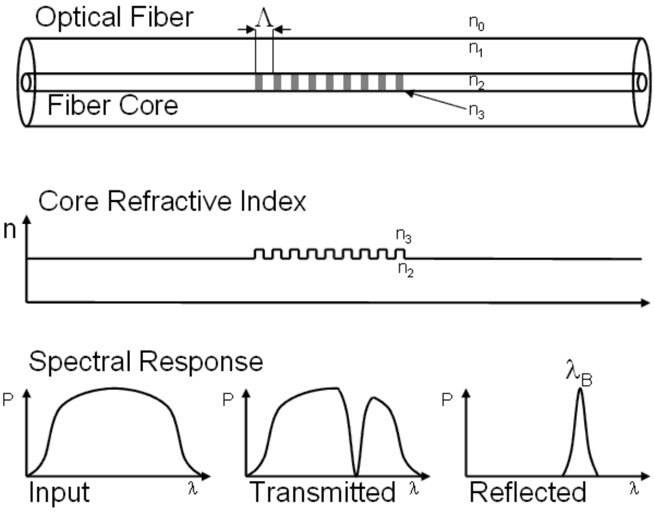

Figure 1: FBG structure and operation (Wild & Hinckley, 2008).

Method

The first task is the characterization of the FBG in terms of the Bragg wavelength and the width and shape of the Bragg reflection peak (the inverse of the transmission peak). This is performed by projecting the output of a tunable laser, for varying laser wavelength, through the FBG, and recording the power output of each of these signals transmitted through the FBG as determined using an Optical Spectrum Analyzer, as shown in Figure 2. The Bragg wavelength can then be established as the wavelength which transmitted the minimum power. The results of a typical Bragg wavelength measurement for a specific FBG is shown in Figure 3, which indicates that the Bragg wavelength is 1554.17 nm. Also the total transmission peak width is about $\Delta\lambda(\max) = 1554.37 - 1544.06 = 0.31$ nm.

To use the FBG as a sensor, a single laser wavelength is chosen that is greater than (or less than) the Bragg wavelength, as an increase in the Bragg wavelength will be indicated by a decrease in the transmitted optical power, and vice versa.

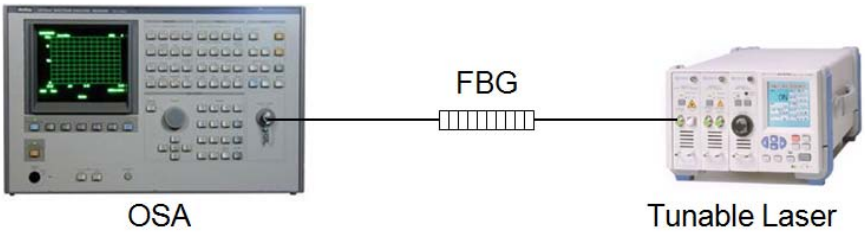

Figure 2: Experimental setup for FBG characterisation measurements.

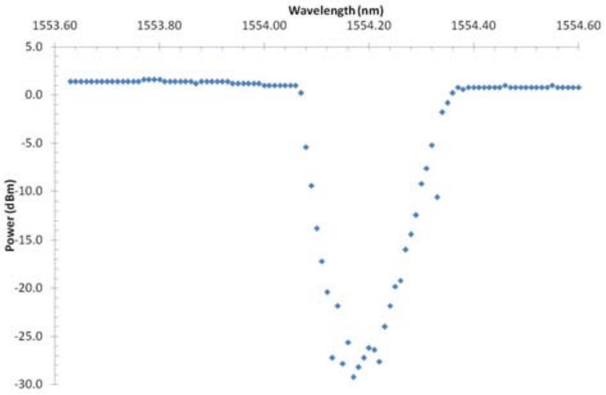

Figure 3: FBG transmitted optical power as a function of laser wavelength.

Temperature studies were performed by immersing the optical fibre containing the FBG into a container of water, which was heated using a hotplate. The water temperature (measured with a simple liquid-in-glass thermometer) was varied, and the transmitted power recorded for a single specific laser wavelength. The temperature range chosen was initially 0°C to 80°C in 5°C increments to establish a temperature range in which the variation of the transmitted power is of a linear nature and can be easily modelled. Once this range is established, a more precise set of data is recorded over a restricted temperature range in 1°C increments.

In the pressure studies, pressure was applied by placing brass masses on top of the horizontally oriented FBG. The change in the transmitted optical power then relates to the shift in the Bragg reflection peak relative to the fixed laser wavelength greater than the Bragg wavelength, due to the applied mass.

Results – Temperature Measurements

The two control experiments were performed with a single mode fibre (without FBG), to determine the temperature sensitivity of a fibre, and the effects of water immersion on the fibre performance. This was done to ensure the students understand that other factors can affect the experiments, and hence must be controlled. Since the temperature was to be measured in water, giving a consistent temperature, the affect of submerging the optical fibre in water need to be determined. The use of a large beaker of water also meant that a significant length of fibre would also be submerged in the water, hence the temperature stability of bare fibre was measured. For a laser wavelength of 1554.36 nm, the temperature dependence of optical power was determined to be $P_{\mathrm{SMF}} = -0.0015T + 3.98$ dBm. Also, the variation in optical power as a function of immersion time in water is $P_{\mathrm{SMF}} = 0.0069t + 3.91$ dBm, with t in minutes. These results show that there was little correlation between the transmitted power and temperature, or exposure to water absorption, for a single mode fibre.

Figure 4(a) shows the effect of temperature over a range of 20°C to 80°C on the optical power transmitted by the FBG for a laser wavelength of 1554.36 nm. The fact that the power decreases and then increases within a small temperature range indicates that the Bragg wavelength is definitely increasing as temperature increases. Also, the width of the transmission peak, which extends from about 20°C to 50°C ($\Delta T = 30$°C), corresponds to the width of the Bragg peak in Figure 3, which is 0.31 nm. Assuming that there is no strain ($\varepsilon = 0$), and using $\Delta T = 30$ °C, $\Delta\lambda_B = 0.31$ nm, and $\lambda_B = 1554.17$ nm, we can use equation (2) to determine the temperature coefficient as $C_T = 6.65 \times 10^{-6}$ /°C. As expected, the positive value of C_T indicates that the Bragg wavelength increases with an increase in temperature, however, the average optical density could be affected by temperature. From equation (1), a change in n would change the Bragg wavelength if the grating period was held constant. It is expected that an increase in temperature would bring about an increase in optical density, and therefore an increase in the value of n. Taking this into account, the increase in the Bragg wavelength was not entirely caused by thermal expansion, but also by the increase in the average refractive index.

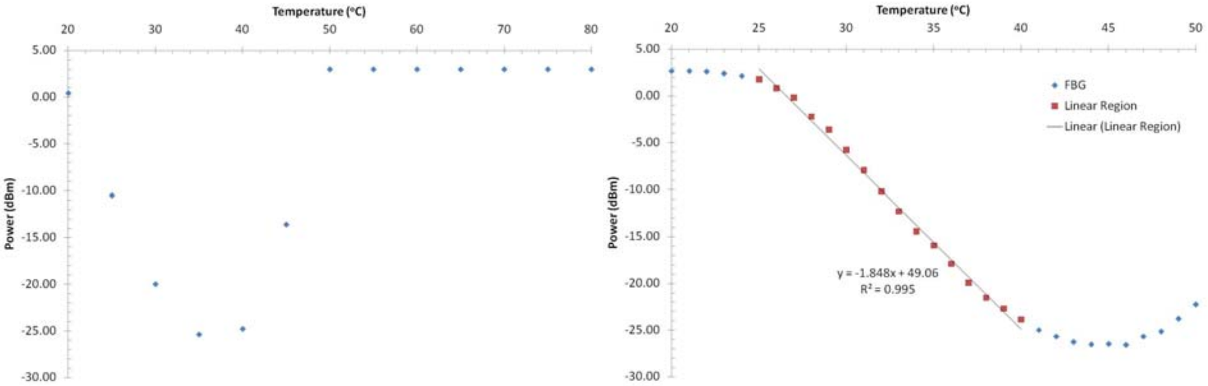

Figure 4: (a) Low resolution and (b) high resolution temperature sensitivity of the FBG.

Figure 4(b) shows the high resolution temperature measurements, using a laser wavelength of 1554.40 nm, for a temperature range of 20°C to 50°C. There is a linear relationship between the transmitted optical power and a change in temperature between 25°C and 40°C. The FBG is 1230 times more sensitive to a change in temperature than the single mode fibre. The single mode fibre transmission is approximately constant at 3.9775 dBm, with a variation in optical power of less than 1% over the full range of temperature variation. Between 25°C and 40°C, for a 1554.40 nm signal, the sensitivity of the FBG transmitted power to a change in temperature is –1.8486 dBm/°C. Hence, this arrangement can be used to measure temperature, with the temperature being related to the measured optical power transmitted by the FBG as $T(^{o}\mathrm{C}) = 26.5412 - 0.5409 P_{\mathrm{FBG}}(\mathrm{dBm})$ in the range of 25°C to 40°C.

Results – Pressure Measurements

For the pressure measurements, a laser wavelength of 1554.28 nm was used. For large masses (100 to 1100 grams), the relationship between mass and power was not always consistent, as the correlation coefficient for the data regression analysis was poor ($R^2 < 0.9$). For large masses, the change in optical density produces a large enough change in the refractive index of the fibre for it to have a significant effect on the transmitted optical power. For small masses (5 to 50 grams), shown in Figure 5, the correlation coefficient is acceptable ($R^2 = 0.9344$), which suggests that the effect of mass on refractive index change is negligible for this mass range. Figure 5 indicates that for a mass range of up to 50 grams, the FBG will act as an effective mass (or force/pressure) sensor. The transfer function relating optical transmitted power to mass is $P_{\mathrm{FBG}} = -0.1563m$, with a sensitivity of –0.1563 dBm/gram.

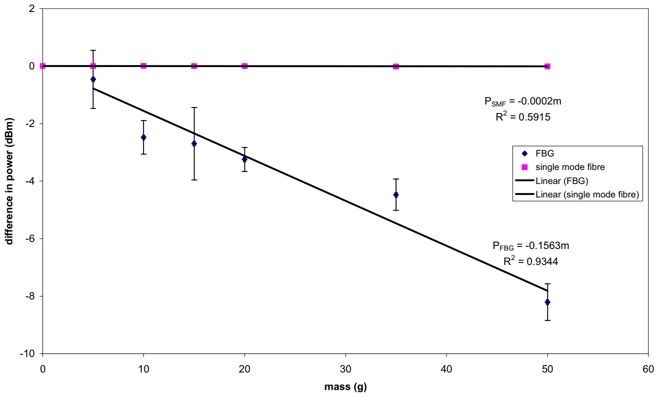

Figure 5: Mass sensitivity of the FBG.

We can estimate the stress coefficient of the FBG using equation (2). Measurements are performed at constant temperature ($\Delta T = 0$), so that the second term in equation (2) is negligible. Rearranging equation (2) we obtain for the stress coefficient, $C_\varepsilon = \Delta\lambda/\lambda\varepsilon$, where the transverse strain in the FBG is $\varepsilon = \sigma/E$, the axial stress (pressure) applied is $\sigma = F/A$, Young's modulus of the FBG is $E = \nu\sigma/\varepsilon$, the force applied is $F = mg$, and the area over which the force is applied is $A = l_n \cdot W_f$, where l_n is the length of the FBG and W_f is the width of the fibre. For $m = 0.05$ kg, $g = 9.8$ m/s^2, $\nu = 0.17$, $W_f = 250$ µm, $l_n = 0.03$ m, E = 73 GPa, $\Delta\lambda = 0.02$ nm, and $\lambda = 1554.09$ nm, the FBG stress coefficient is $C_\varepsilon = 84.50$.

Project Evaluation

After completion of their project, students made very positive comments during the feedback survey. A selection of student comments included: "I found the research scheme to be a real eye opener for me, as well as a thoroughly enjoyable use of the weeks in which I participated." "I found working with the scientists and fellow students allowed me to learn a lot about scientific methods and get an idea about what research is like." "The project was very enjoyable and insightful." "Being a research scientist was a lot of fun, though at the same time required patience to persevere through the tedious repetition that is required for accurate results. However, in the end the outcome was very rewarding." "The applications of the project and the idea of using light instead of electricity as a way of transmitting information was very interesting to me, and I am very glad I had the opportunity to be part of the programme."

As assessed by the supervising academic staff, all of the secondary students performed at a level equivalent to that of a credit or distinction grade second-year engineering undergraduate student, despite their lack of background to the material of the project or pre-requisite training usually provided to undergraduate students. One explanation for why the secondary students were able to perform at advanced undergraduate standard is the nature of the research projects. The student researchers were able to work fulltime at their own pace under the guidance of an experienced researcher. Undergraduate students are often under considerable time pressure to produce results, have competing interests from other units/courses they are studying, and must share access with other students to their supervisor. This aspect needs further study to develop a programme that can be incorporated into undergraduate research-based training to improve student outcomes.

All four students eventually went on to university study at one of the tertiary institutions in WA, with three enrolling in science or engineering degrees and one in arts. The inquiry based learning method used in the research projects allowed students to perform at their own pace over the period of the project, and even though their background in optical fibres was limited, they quickly picked up the concepts involved by studying the practical applications of the FBG sensors. Overall, this limited programme has been a success, as evidenced by the feedback from the participating students, and their level of achievement despite their limited background and understanding.

Conclusions

We have reported on results obtained from a program of research-based projects for secondary students on FBG optical fibre sensors applied to the measurement of temperature and pressure. Based on a series of simple measurements of transmitted optical power for a fixed laser wavelength, it is possible for student researchers to develop an extensive knowledge of the behaviour and performance of these types of sensors. Despite their lack of knowledge in this field, the secondary student researchers were able to demonstrate the development of good research, problem solving and communication skills. Feedback from the students showed a considerably degree of satisfaction and enjoyment in their involvement in this programme. This lends support that this type of learning method is suitable for translation to undergraduate engineering learning activities. Based on this success, we intend to introduce elements of this programme into second year engineering and aviation instrumentation-based units, and have been awarded an IEEE Instrumentation and Measurement Society Course Development grant for 2011-2012 for this purpose.

References

Archambault, J.L. Reekie, L., & Russell, P.S.J. (1993). 100-percent reflectivity Bragg reflectors produced in optical fibres by single excimer-laser pulses. *Electronics Letters*, 29(5), 435-455.

Arsenault, J., Godsoe, S., Holden, C., & Vetelino, J. (2005). Integration of sensors into secondary school classrooms. In *Proceedings of the 35th ASEE/IEEE Frontiers in Education Conference*, (pp.33-38). Piscataway, NJ: IEEE Press.

Bachnak, R., Sadovsky, A., Jefferess, G., & Lyle, S. (2006). Applied research offers undergraduate students experience and ideas for projects. In *Proceedings of the IEEE 36th Annual Frontiers in Education Conference*, (pp. M3G-1 to M3G-6). Piscataway, NJ: IEEE Press.

Celebi, H., & Qaraqe, K.A. (2011). Engagement of undergraduate students in advanced research: a case study. In *Proceedings of the 2011 IEEE Global Engineering Education Conference*. (pp.529-532). Piscataway, NJ: IEEE Press.

Carnegie, D.A., Watterson, C., Edwards, J., & Exley, T. (2011). Increased engineering awareness through targeted outreach. In *Proceedings of the 2011 IEEE Global Engineering Education Conference*, (pp.128-135). Piscataway, NJ: IEEE Press.

Curriculum Council, Western Australia (2005). *Curriculum framework progress maps – science*. Osborne Park, WA: Curriculum Council WA.

Dawes, L., & Rasmussen, G. (2007). Activity and engagement – keys in connecting engineering with secondary school students. *Australian Journal of Engineering Education*, 13(1), 13-20.

Gregg, J., & Chen, T. (2005). PEER: enriching secondary engineering education through a college summer camp. In *Proceedings of the 2005 IEEE Conference on Microelectronic Systems Education*, (pp.1-2). Piscataway, NJ: IEEE Press.

Harsanyi, G., & Lepsenyi, I. (2000). Sensors' education and related student research projects. In *Proceedings of the IEEE 2000 Electronic Components and Technology Conference*, (pp.1034-1041). Piscataway, NJ: IEEE Press.

Hill, K.O. (1978). Photosensitivity in optical fiber waveguides: application to reflection fiber fabrication. *Applied Physics Letters*, 32, 647-649.

Hollow, R.P. (2000). The student as scientist: secondary student research projects in astronomy. *Publication of the Astronomical Society of Australia*, 17, 162-167.

Kane, D.M. (2009). Optoelectronic technology profiles – motivating and developing research skills in undergraduate students. In *Education and Training in Optics and Photonics*, OSA Technical Digest Series (CD) (Optical Society of America, 2009), paper EMB5.

Le, K.N., & Tam, V.W.Y. (2010). How to retain postgraduate students in engineering programmes: a practical perspective. *European Journal of Engineering Education*, 33(5-6), 511-524.

Mills, J.E., & Treagust, D.F. (2003). *Engineering education – is problem-based or project-based learning the answer?* Australasian Journal of Engineering Education. Accessed at http://www.aaee.com.au/journal/2003/mills_treagust03.pdf on 20 July 2011.

National Science Foundation (2011). Accessed at http://www.nsf.gov/crssprgm/reu/index.jsp on 29 July 2011.

Othonos, A., & Kalli, K. (1999). *Fiber bragg gratings: Fundamentals and applications in telecommunications and sensing*. Norwood, MA: Artech House.

Sherry, R.A., & Lord, S.M. (1997). Design of a laboratory experiment on optical fiber and applications in fiber sensors. In *Proceedings of the IEEE 27th Frontiers in Education Conference*, (pp.756). Piscataway, NJ: IEEE Press.

UNESCO (2005). *Engineering: Issues Challenges and Opportunities for Development*. Fontenoy, France: UNESCO Publishing.

Vengsarkar, A.M., Murphy, K.A., & Claus, R.O. (1992). Stable phase-modulated fiber-optic sensors for senior electrical engineering laboratory curricula. *IEEE Transactions on Education*, 35(1), 69-75.

Villanueva, M., Cufi, X., ElFakdi, A., Ridao, P., & Garcia, R. (2010).Attracting talent to increase interest for engineering students among secondary school students. In *Proceedings of the 2011 IEEE Global Engineering Education Conference*, (pp.347-353). Piscataway, NJ: IEEE Press.

Wild, G., & Hinckley, S. (2007). Fiber Bragg grating sensors for acoustic emission and transmission detection applied to robotic NDE in structural health monitoring. In *Proceedings of the 2007 IEEE Sensors Applications Symposium*, (pp. 1-6). Piscataway, NJ: IEEE Press.

Wild, G., & Hinckley, S. (2008). A transmit reflect detection system for fibre Bragg grating acoustic emission and transmission sensors. In S. C. Mukhopadhyay and G. S. Gupta (eds), *Smart Sensors and Sensing Technology*, (183-197). Berlin, Germany: Springer-Verlag.

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