

Investigation of the Effect of Bonding Points on Metal Surface-Mounted FBG Sensors for Electric Machines

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Abstract—Fibre Bragg Gratings (FBGs) offer several advantages including their immunity to electromagnetic fields making them excellent in situ sensors for feature extraction in electrical machines condition monitoring. However, the pre-requisite of bonding FBGs circumferentially on either the machine cast frame or stator windings can introduce undesired sensing characteristics. This is because the FBG relies on adhesives as the transfer medium for any sensed parameter between the machine and sensor. Whilst FBG sensors rely mainly on wavelength shift, an intolerably low signal-to-noise ratio will result in difficulty in measuring such shifts. As a complementary signature, differential optical power can be combined with wavelength shift to broaden the feature extraction capability of FBG sensors. This makes power level (dBm) an important sensing parameter for FBG sensors. The effect of varying number of bonding points on transmitted optical power is investigated using unstripped and stripped bare fibres as well as an actual FBG sensor. Increasing the number of bonding points beyond an optimum number has been observed to significantly attenuate the optical signal power level and quality for a given dynamic range. Hence, as the number of bonding points is increased, the level of attenuation should be closely monitored to ensure that the optimum number is not exceeded if excellent and accurate FBG sensing characteristics are to be realised.

1. INTRODUCTION

Fibre optic sensing (FOS) has been successfully used for structural health monitoring (SHM) and is currently being explored for other condition monitoring applications such as biomedical sensing and online condition monitoring (OCM) of electrical machines. In electric machines monitoring, most conventional sensors are usually bulky, require electrical power to work, and may be difficult to install in certain desired locations within the machine. Multi-signature sensing in electric machines typically involves the use of multiple sensors, whose operations are oftentimes affected by electromagnetic interference (EMI). Thus, FOS is being adopted to overcome the aforementioned demerits of conventional machines sensors. In [1] for instance, multiple sensors were multiplexed onto a single fibre for simultaneous measurements of several machine signatures. Advantages of fibre optic sensors include high accuracy, high bandwidth, wide temperature range, easy installation without recalibration requirements, small size and weight, immune to electromagnetic interference (EMI), suitable for hazardous environments, chemically inert even against corrosion, low power consumption, amongst others [2, 3]. In electrical machine applications, where the environment is rich of electromagnetic waves, the most important property of the fiber optic sensors is the immunity to any electromagnetic interference regardless of the frequency. The fibers are only carriers of the light but do not interact with the light. As a sensor, the fiber itself cannot sense anything but will only transmit

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and reflect the light passed through. However, an external influence on the fiber such as vibration or temperature will result in a wavelength shift of the light without altering its spectral profile.

Fibre Bragg gratings (FBG) are one form of sensors commonly used in FOS because of their simple but effective multi-signature sensing capability when multiplexed on a single fibre. FBGs are apposite for distributed sensing and redundant measurements thus, increasing sensor reliability and robustness with insignificant additional cost. FBG sensors used in electric machines are bonded to a metallic surface (either around the cast frame or on the stator windings; [4–11]) using an adhesive. One rare exception is the use of rotary joints with FBGs [12] which is an uncommon application. The bonding is required in order to allow the gratings to make contact with the machine structure from which desired features or signatures can be sensed. Thus, the bonding serves as the *sole* transfer medium between for the sensed machine parameter. However, it is difficult to know how much adverse effect the bonding has on the FBG sensing characteristics. [13] identified glue material properties, anisotropy and aging problem as important factors that affect the reliability and sensitivity of optical fibre sensors. If multi-signature with distributed sensing were to be achieved, there will be multiple bonding points. It is imperative then to know how the increase in the number of bonding points affects the sensitivity and reliability of FBGs. Therefore, investigating the effect of adhesive bonding is crucial in proving the credibility of FBG measurements when used for signature extraction in the OCM of electrical machines.

2. FBG SENSING PRINCIPLE

FBG sensors are based on the Fresnel effect and Bragg shift principle. As described by [3], guided light transmitted along a fibre core comes in contact with inscribed gratings resulting in each grating weakly deflecting the light by Fresnel effect. For silica material used to make optical fibres, the distance travelled by light is affected by the material's refractive index, n , such that:

$$2n_{eff}\Lambda = \lambda_B \quad (1)$$

λ_B is the Bragg wavelength, Λ the periodicity of the grating, and n_{eff} the effective refractive index of the fibre determined by the average of the refractive index of the fibre core and the refractive index of the fibre cladding [3]. By varying either the fibre's effective refractive index or the grating periodicity or both, a change in the Bragg wavelength is achieved known as Bragg Shift. Two factors that affect both n_{eff} and Λ , thus capable of causing Bragg shift are strain (photo-elastic effect) and temperature (thermos-optic effect) [3]. When an FBG sensor is bonded to a host structure and the latter experiences some external force (say, mechanical vibration or thermal agitation), there is some proportional strain on the gratings. This causes a proportional shift in the wavelength of the FBG as shown in Figure 1. The sensitivity of FBG to strain and temperature can be represented by:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - \rho_e)\varepsilon_z + (\alpha + n)\Delta T \quad (2)$$

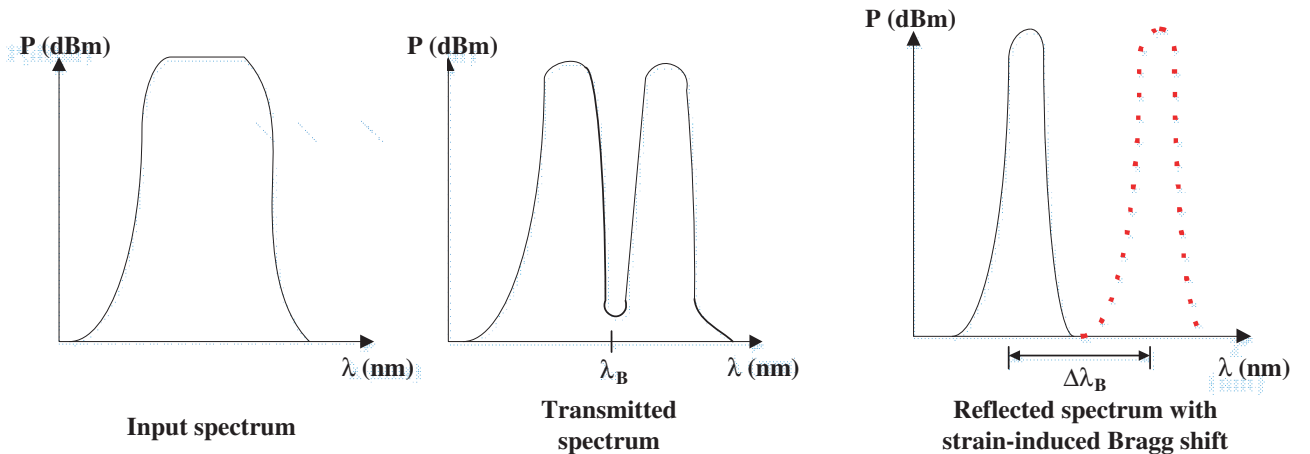


Figure 1. Bragg shift sensing principle of FBG.

ρ_e is the photo-elastic coefficient; ε_z is the longitudinal strain of the grating; α is the thermal expansion of silica; and n is the thermo-optic coefficient [3]. A demerit of the FBG as a sensor is its cross-sensitivity to both strain and temperature, for which a suitable compensation scheme should be adapted to reduce any errors in measurements.

3. WAVELENGTH AND POWER LEVEL SIGNATURES

Using an optical spectrum analyser (OSA) to display an FBG sensor measurement usually outputs wavelength shift ($\Delta\lambda_B$) and power level (dBm) signatures. It is common to use the spectral Bragg shift as the only FBG signature for condition monitoring applications. The power level (dBm) or optical signal amplitude is often regarded as not crucial. The caveat to this generally accepted idea is the fact that the *dynamic range* of any optical analyser plays a significant role in determining if the spectral shift being measured has been compromised by noise. The dynamic range is the difference between the reference power level chosen to display the FBG spectrum, and the noise floor, thus it determines the signal-to-noise ratio (SNR). For an intolerably low SNR, the FBG wavelength shift becomes difficult to measure due to adverse impact of noise on the sensor output. This makes power level considerably important. The power level can also be used as a separate but complementary machine signature for condition monitoring in order to achieve multi-signature feature extraction using differential optical power (DOP). DOP compares the variation in power level due to strain or temperature on the gratings, thus providing additional information to the wavelength shift of FBGs. Multi-signature feature extraction is important especially in OCM of machines because there is a consensus that there exists no single fault signature that is able to detect all possible failures within a machine [14]. The simultaneous use of multi-signature for robust and effective OCM has been investigated in few research works. Given that the power level (dBm) before say vibration sensing is P_{bv} and the power level following a machine fault is P_{ff} , then DOP is given by,

$$\Delta\text{DOP} = P_{bv} - P_{ff} \quad (3)$$

By mapping $\Delta\lambda_B$ and ΔDOP signatures, more information of the condition of the machine can be deduced than relying solely on $\Delta\lambda_B$. Thus, the power level becomes a crucial complementary parameter in utilising FBG as sensors. However, this power level can be attenuated by bonding. This work focuses on the investigation of the effects of the bonding points on the power level of the transmitted optical signal through the fibre core of FBG; and how these effects alter an FBG spectrum as an indication of any impact on its performance.

4. EFFECTS OF BONDING

Bonding using adhesives has become crucial in the implementation of FBG sensors in order create contact between the gratings and the machine. To achieve point or distributed sensing, single or multiple bonding points would be respectively created. In the case of electric machines, it is expected that the strain sensed by the FBG should be proportional to the machine signature being monitored. However, the existence of the adhesive point and protective coating (if any), converts part of the strain into shear deformation [15–17] identified the bonding point as a direct factor which distorts the reflection spectra of FBGs by causing stress birefringence, i.e., change in both the polarisation and direction of propagation of light. [18] further submits that undesirable effects caused primarily by bonding points are present which affect the sensing characteristics of FBG strain sensors especially during their fatigue process. As a result of the crucial role of the bonding point as a strain transfer medium between the machine and the FBG sensor, it has great influence on the optical transmission rate of the latter [19–21]. In civil engineering applications, [22] suggested that where adhered FBG strain sensors are used, an error rate of about 5 ~ 10% with a correction coefficient of about 1.05 ~ 1.11 should be considered. In other non-machines applications, the impact of geometric properties as bonding length, thickness and material properties on FBG sensitivity, particularly in the context of the strain transmission functionality of bonding points was investigated by [16, 20, 23–26]. Generally FBGs can be either surface mounted onto or embedded within the measured component [27]. However, the former has been repeatedly used in most research works associated with FBG-in-machines, thus making surface-mount FBGs apposite for

OCM of electrical machines.

$$\gamma = \frac{U_S - U_F}{t_B} \quad (4)$$

$$\varepsilon_S = \frac{dU_S}{dx} \quad (5)$$

$$\varepsilon_F = \frac{dU_F}{dx} \quad (6)$$

In order to characterise the bonding layer under the assumptions of a continuous displacement and stress across the FBG-host structure interface, [28] used a one-dimensional model as shown in Figure 2. The strain-displacement relationships as deduced by [28] were given by:

U , ε , and γ are the displacement, normal strain, and shear strain, respectively. Subscripts S , F , and B stand for host structure, FBG, and Bonding layer, respectively. The analytical model in [28] suggests that the effectiveness of the FBG strain transfer via bonding strongly depends on the shear modulus of the adhesive, the thickness of the bonding layer, and the bonding length. [28] further submits that an unacceptable bonding layer would fail to transfer enough strain from the host structure to the FBG sensor.

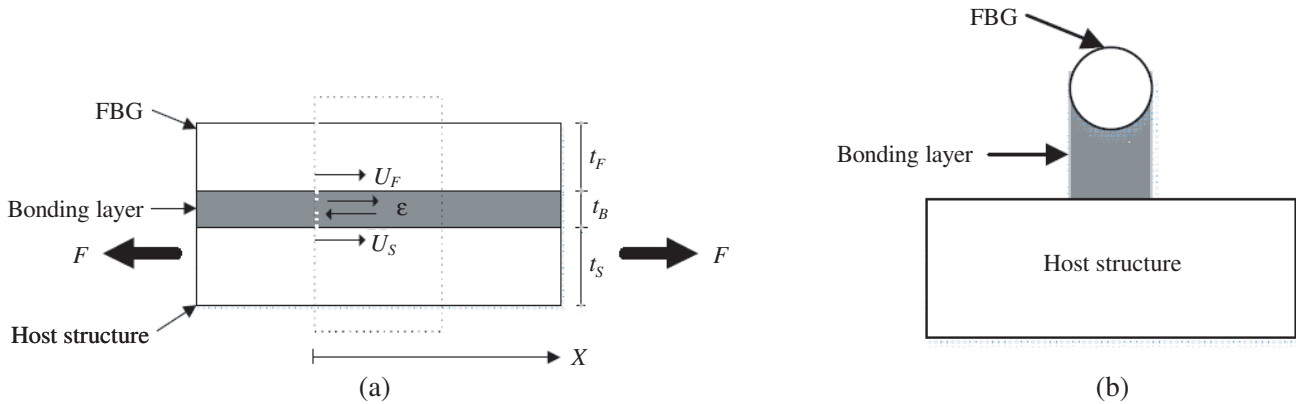


Figure 2. Host structure with a surface-bonded FBG [28]. (a) One-dimensional free-body diagram. (b) Cross-sectional view.

For electrical machines applications, as the FBG sensors will usually be bonded to some metallic surface (cast frame or stator windings), the effects of the bonding points ought to be investigated. Such investigation will fully assess sensor reliability and determine if there is a limit to the number of bonding points that can be created per fibre in FBG-in-machines OCM systems. It is noteworthy that the scope of this investigation looks at the effect of having multiple bonding points on the sensing characteristics of a surface-mount FBG prior to subjecting it to external forces such as the high dynamic strain, vibration and thermal cycling operating conditions of an electric machine.

5. EXPERIMENTAL METHOD

Multi-point sensing is standard in any industrial distributed parametric sensing for robustness via redundancy. Thus, if the multiplexing benefits of FBG sensors were to be fully derived, then the effects of multiple bonding points must be investigated. The effects of bonding were investigated using a circular metallic plate with a diameter of 179 mm similar to that of a 2.2 kW induction machine test rig shown in Figure 3. Three cases were investigated with the first two having up to ten bonding points, and the third used to affirm the outcome of the earlier cases. In the first case (unstripped case), the cladding of an optical fibre was bonded on to the circular metallic plate, with the number of bonding points increased from one to ten. The second case (stripped case) was very similar except that the cladding of the optical fibre was stripped. The reason for investigating both cases was because an



Figure 3. Experimental set up showing a circular metal plate with the same diameter as a 2.2 kW induction machine having fibre bonded on to it at multiple points and connected to the OSA and LabView.

FBG would usually be fabricated on a stripped fibre but could be very easily recoated after fabrication. Thus, understanding the effect multiple bonding points would have on both conditions provides a useful information as to if recoating an FBG is crucial for performance-related reasons. In the third case, an actual FBG was then bonded onto the circular metal plate with the number of bonding points limited to the optimal number observed during the first and second cases. Cases I and II initially studied the effect of increasing bonding points on optical power level in order to estimate the optimum number, if any, of bonding points for a given dynamic range.

Case III uses the observations from previous cases to implement the optimum number of bonding points for a given FBG sensor. A Hewlett Packard (HP) optical spectrum analyser (OSA) Model No. 86142A which has a dual-function as the light source as well as the analyser was used. A National Instrument GPIB-USB-HS adapter was used to acquire numerical data from the OSA via a LabView 2014 environment on a Windows 7 computer. Table 1 shows the OSA configuration used for each of the three cases, and a similar graphical scaling was used in the LabView graphical user interface (GUI) application. Loctite 416 was used as the adhesive because of its suitability for metals and has a flash point of 80–93°C. It has a fixture time of between 20 and 40 seconds. For larger industrial machines operating at higher temperatures, a suitable adhesive with a much higher flash point should be used to avoid weakening of the bonding due to reduced viscosity.

Table 1. OSA configuration.

Parameter	Setting
Centre wavelength, λ	1550 nm
Reference level	–55 dBm
Span	5 nm
Scale per division	5 dB
Dynamic Range	–25.63 dB

The setup procedure for cases I and II experiments is as follows:

- i: Prepare the bare fibres (stripping its ends, cleaning, cleaving,) and connect both ends to two bare fibre connectors;
- ii: Connect light source and OSA input using a patch cord to confirm signal transmission;
- iii: Connect each fibre with the bare fibre connectors to the OSA to obtain a reference optical output without any bonding point(s);
- iv: Apply the adhesive one point on each of the two fibres, allow to cure; and then reconnect to the OSA one at a time;

Table 2. Power loss with increasing bonding points.

Normalised average power loss after bonding (dB)			Distance between bonding points (mm)	Bonding points
Unstripped	Stripped	FBG		
-1.75	-0.5	0	-	0
-8.5	-8.75	-	1	1-2
-8.75	-8.5	-	10	2-3
-7	-13	-2	1	3-4
-13.25	-4.5	-	10	4-5
-6.5	-10.75	-	1	5-6
-8.8	-10.5	-10	10	6-7
-17.5	-20.25	-	1	7-8
-18.5	-17.5	-	10	8-9
-19	-19.5	-	1	9-10
-19	-18.75	-	11.2	10-1

v: Store the corresponding OSA results for a single bonding point for each scenario using ‘write to file’ in LabView.

vi: Repeat step iv and v sequentially to create up to 10 bonding points for each fibre sample. The distance between two consecutive bonding points being about 10 mm whilst the spacing between each pair of bonding points being about 100 mm as shown in Table 2.

For case III:

vii: Based on the observations from cases I and II, create a set of three bonding points with an actual FBG sensor similar to step iv.

viii: repeat step v.

ix: repeat step vii and viii.

Splicing of pigtails was not preferred in this experiment as compared to the use of bare fibre connectors because of the number of repeated steps as the number of bonding points increased for each sample. This would have required several splicing each time a new bonding point is created. An electric heater was used to ensure the adhesive was properly cured before each reconnection to the OSA in order to ensure the bonding points were sufficiently effective. The FBG used in this work was fabricated in-house using the phase mask technique in the clean room of Aston Institute for Photonics Technologies (AIPT) with a centre peak of wavelength of around 1550 nm.

6. DISCUSSION OF EXPERIMENTAL RESULTS

With only patch cords connected to the dual function OSA, the dynamic range and reference power level based on the configuration in Table 1 were -25.63 dB and -55 dBm respectively. The dynamic range which is dependent on the OSA resolution, gives an idea of how much attenuation the optical signal undergoes with increasing number of bonding points. Factors such as imperfect fibre preparation and termination were expected to cause some dB loss in the transmitted optical signal and this has been taken into consideration during the experiment. After the connection of the unstripped fibre using two bare fibre connectors, a loss of about -1.75 dB was observed without any bonding point, thus transmitted power was around -56.75 dBm. This loss can be attributed to the difference in loss characteristics between the patch cords and the unstripped fibre. Additional losses were incurred with the use of bare fibre adapters rather than spliced pigtail. As earlier explained it was preferable to use bare fibre adapters instead of spliced pigtails to avoid too many splicing. With the creation of bonding points, there was a very clear observation of increasing power loss and signal attenuation. The average power loss when an additional bonding point is created is shown in Table 2.

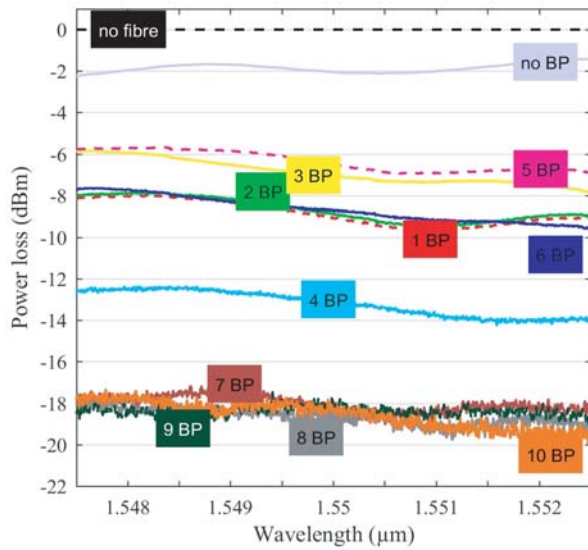


Figure 4. Unstripped fibre bonding layer (BL) characteristics: comparison of optical signal transmission with increasing number of bonding points.

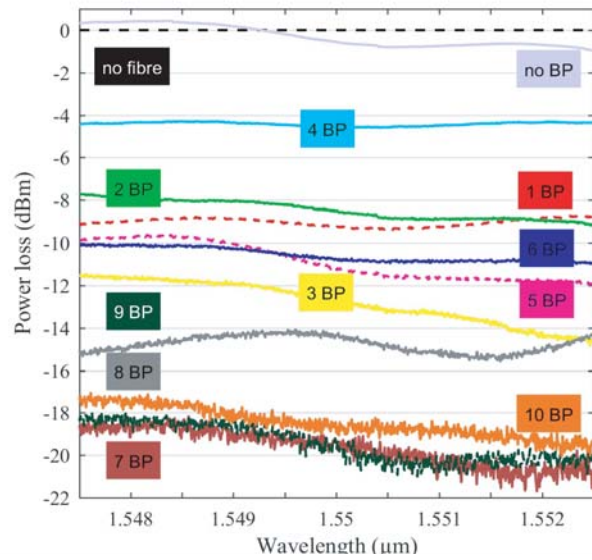


Figure 5. Stripped fibre bonding layer (BL) characteristics: comparison of optical signal transmission with increasing number of bonding points.

The increase in power loss with increasing number of bonding points for the unstripped fibre is shown in Figure 4. An interesting observation was that as the power loss increased and approached the dynamic range, the optical signal quality attenuation became more obvious. Up to the 6th bonding point, the signal loss was less than -10 dB which is less than half the dynamic range. As seen in Figure 4, the signal still looks reasonably good in quality. Few anomalies were observed in the measurements for the 4th bonding point which had higher losses than its succeeding bonding point. This could be as a result of fibre preparation, however, for the 4th BP, the average loss was about -13.25 dB which is just above the mid-point of the dynamic range with the signal quality still looking reasonably good.

The 7th, 8th, 9th, and 10th looked adversely attenuated in quality by noise; thus, for the unstripped fibre, the optimum number of BP is six for a -25.63 dB dynamic range. The total transmitted power after the creation of six bonding points was about -68.25 dBm compared to the reference -55 dBm which is an estimated total loss of -13.25 dB.

Test results for the stripped fibre without any bonding point revealed a loss of about -0.5 dB. The average power loss when an additional bonding point is created for the stripped fibre scenario is also shown in Table 2 while the increase in power loss with increasing number of bonding points for the stripped fibre is shown in Figure 5.

A similar observation was made on how the optical signal quality attenuation became more obvious as the power loss increased and approached the dynamic range. As seen in Figure 5, the signal still looks reasonably good in quality up to the 6th BP. Few anomalies were also observed in the measurements for the 1st and 3rd BPs which recorded higher losses than their succeeding BPs; as well as the 4th BP which recorded the opposite. But regardless of the anomalies, the average loss as at the 6th BP was about -10.5 dB which is still above the mid-point of the dynamic range with the signal quality still looking reasonably good.

On the other hand, the 7th BP average loss was about -20.25 dB, and the signal quality appeared to have been significantly attenuated by the noise floor. The 8th and 9th BPs looked affected as well with average losses of about -17.5 dB and -98.5 dB respectively, the signal quality appear compromised by the noise floor when compared to the 1st through the 6th BPs. The 10th looked even more adversely attenuated in quality by noise; thus, for the stripped fibre, the optimum number of BP is six for a -25.63 dB dynamic range. The total transmitted power after the creation of six bonding points was about -66 dBm compared to the reference -55 dBm which is an estimated total loss of -11 dB. A

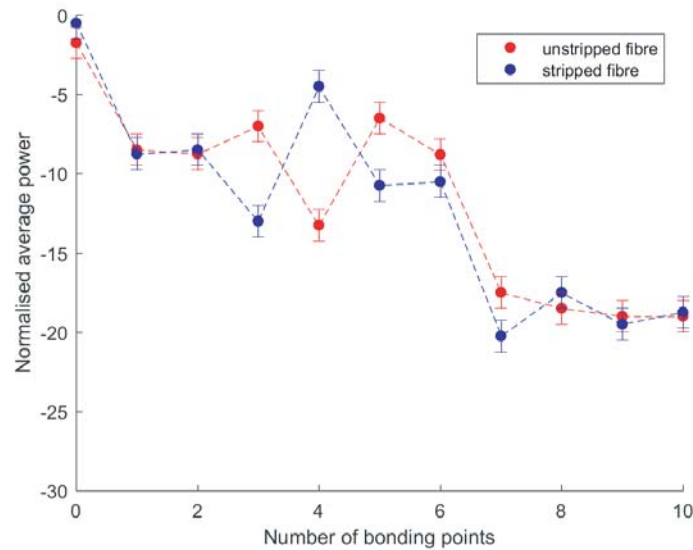


Figure 6. Variation of average power loss (dB) with increasing number of bonding points for unstripped and stripped fibres for a dynamic range of -25.63 dB.

difference of -2.25 dBm in total transmitted power and average loss difference of -2.25 dB between the unstripped and stripped fibre with the same optimum number of BPs (six) for a -25.63 dB dynamic range was observed. An inference to be drawn from the use of stripped fibre is how crucial is the recoating of an FBG sensor after fabrication. If recoating appears to be crucial, then the precise FBG sensor location must be known without doubt before and after any recoating process. Based on the results, recoating of FBG is not as crucial as initially thought but would be desirable for increased physical protection of the gratings. The effects of stripping is not as crucial as the effects of increasing number of bonding points in this experiment because the FBGs can be easily recoated to eliminate any attenuation of the optical signal due to stripping. However, stripped fibre is more susceptible to mechanical and physical damage than a recoated FBG. The scatter plot and linear retrogression fit in Figure 6 clearly show that there is a non-linear signal attenuation with increasing bonding points during optical signal transmission. Eight out of the 20 bonding points plotted fell below the -15 dB average power loss, which is approximately 60% of the dynamic range; giving an average of six (6) as the optimum number of BPs for each case (unstripped or stripped fibre). Clearly in terms of the optimum number of bonding points, there is consistency with both cases.

Test results for the effect of multiple bonding points on an actual FBG sensor revealed consistency with the preceding observations. Spectra for no bonding, 3 BPs and 6 BPs showed increasing attenuation with a maximum loss of about -10 dB between no bonding and six bonding points as shown in Figure 7. The spectral response shows that increasing the number of BPs beyond six would obviously affect the quality of the FBG sensing characteristics. Another observation was that after 6 BPs, the signal quality appeared slightly more compromised for the actual FBG sensor than the bare stripped and unstripped fibres. Table 2 shows the variation of bonding point distance with transmitted power dBm for the FBG sensor. It is important to note that there is no generally accepted standard level/range of dB loss for surface-mounted FBG sensors on metallic surfaces owing to its emerging variety of sensing applications. In addition to the emerging nature of FBG sensing applications, another factor that makes it difficult to standardise loss levels for surface-mounted FBGs is the differing characteristics of various gratings. This is due to differences in fibre doping constituent, grating fabrication method, reflectivity, birefringence behavior, etc. The importance of the dynamic range which is dependent on the specification/resolution of the optical interrogator used to display the FBG sensing spectrum must be highlighted. If the dynamic range were to be increased, it means the noise floor will be lower and the optimum number of BPs would be higher as the signal quality would likely remain acceptable. Thus, the type of OSA used for feature extraction using FBG sensors has the potential of increasing or decreasing the optimum

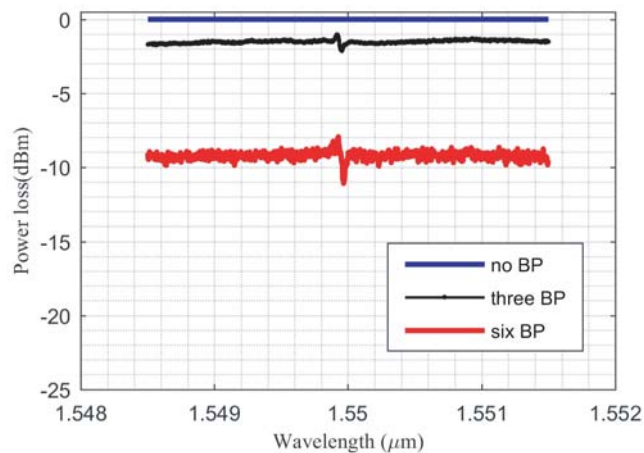


Figure 7. FBG sensor BP characteristics: comparison of an FBG optical signal transmission with 6 bonding points as optimum for a 25 dB dynamic range.

number of bonding points that can be implemented. The optimum number of BPs could be influenced by the type of adhesive used for creating the bonding layer at each point; as well as limit the number of sensing parameters that can be multiplexed on a single fibre carrying multiple FBG sensors. Consistency in the bonding shape could also influence what the optimum number of BPs is. How much will a longer bonding point affect the signal when compared to a shorter, fixed diameter bonding?

The test results hitherto have corroborated the importance of obtaining the optimum number of bonding points in the use of optical fibre sensing techniques for feature extraction in distributed parametric sensing such as in electrical machines. Bonding points introduced as a result of the attachment of the fibre sensor to metallic surfaces have been observed to compromise transmitted signal power level. FBG sensor reliability depends mainly on its signal quality and sensitivity in precisely detecting Bragg shifts with an adhesive acting as its sole transfer medium for measuring the desired machine signature. In addition, applications where power level is the desired machine signature, for instance, differential optical spectral power (DOSP) signature; it becomes more imperative to determine the optimum number of BP for the given dynamic range prior to the FBG sensor installation. This is to ensure that effects of increasing bonding points on the optical signal power and quality transmission do not yield inaccurate sensor output which could have consequences such as undesired downtime and cost implications in the OCM of electric machines in major industries.

7. CONCLUSION

The effects of multiple bonding points on optical fibre sensors, particularly the surface-mount FBG type, have been investigated using unstripped (with cladding), stripped (without cladding) and an actual grating sensor. Each fibre sample was bonded circumferentially around a metallic plate of similar diametric dimension to a machine test rig, to emulate FBG installation in the OCM of electric machines. Test results have shown that nonlinear attenuation of optical signal occurs with increasing number of bonding points, necessitating the need to determine the optimum number of BP required for any given dynamic range. This is crucial in the realisation of reliable distributed sensing and condition monitoring of systems involving the use of surface-mount FBGs as in OCM of electric machines. The largest optical power loss was observed in the stripped fibre case, although the disparity was not significant compared with the unstripped fibre. What was significant was that for a dynamic range of -25.63 dB, the optimum number of BPs, regardless of whether it has been stripped or not, was six. Beyond 6 BPs, the signal attenuation compromised both power level and signal quality. Another significant inference drawn was that a higher resolution OSA offering a wider dynamic range would increase the optimum number of bonding points for the same conditions. This experiment further revealed that recoating of FBG after fabrication would not offer any significant merits over a non-recoated FBG sensor within the

context of the effect multiple bonding points would have, except for the additional mechanical outer protection layer it offers. Similar sized bonding (same length and/or little or no diameter variation) could also improve the optimum number of BPs. FBG sensing applications based predominantly on Bragg shift would rely equally on both signal power level and its signal-to-noise ratio (SNR), i.e., its quality. Differential optical power (ΔDOP) could potentially be explored as a complementary machine signature to the wavelength shifts of FBGs. This thus makes the optimum number of bonding points crucial as it significantly affects optical power level. Therefore, the optimal number of bonding points should be predetermined prior to FBG sensor installation with attention paid to the dynamic range of the OSA being used. The optimum number will vary for different applications as a result of such factors as: fibre characteristics, type of adhesive used for creating the bonding layer at each point, or even the specific parameters to be extracted. This optimum number has the potential of limiting the number of signatures that can be multiplexed on a single fibre carrying multiple FBG sensors.

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