# Finite Element Analysis of a Fiber Bragg Grating Accelerometer for Performance Optimization

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**Abstract:** Sensitivity of a cantilever-mass based fiber Bragg grating (FBG) accelerometer can efficiently be tailored by altering the distance between the axis of the FBG sensor to the neutral axis of the cantilever. To accomplish that in general, a backing patch is used to mount the FBG on the cantilever. Use of finite element analysis to quantify the influence of the material constant (Young's modulus) of the backing patch and its thickness on the sensitivity is presented in this paper. It is explicitly shown that for a specific patch material there is an optimum thickness for which the sensitivity happens to be the maximum. Using this optimum design, a sensitivity ~ 1062 pm/g has been experimentally achieved, the enhancement almost by a factor of three as compared to that of the conventional cantilever-mass FBG accelerometer of similar bandwidth.

**Keywords:** accelerometer, cantilever vibration, fiber Bragg grating.

## 1. Introduction

Fiber Bragg grating accelerometers are widely used in seismic and civil structural measurements where it is required to acquire low frequency, low 'g' signals under harsh environmental conditions, without any influence of electromagnetic fields, with multiplexing capabilities [1],[2]. Amongst the various types of FBG accelerometers, the cantilever based designs are suitable for low frequency measurements with high sensitivity and low cross-axis sensitivity [3]. The cantilever based FBG accelerometers basically comprise of a vibrating cantilever with a FBG bonded on the surface or attached to it. The bending strain of the cantilever is transferred to the FBG which results in a wavelength shift proportional to the strain. The bending strain of the cantilever being proportional to the vertical acceleration, the FBG wavelength shift is a direct measure of the vertical acceleration. For high sensitivity, an inert mass is attached to the cantilever tip. However, the highest achievable sensitivity by conventional cantilever-mass design is insufficient for signals of ultra low magnitude such as those in seismic and civil structural measurements. It is obvious that larger the distance of the FBG from the surface, higher would be the strain experienced by the FBG and thus higher would be the sensitivity.

In our previous work we achieved an enhancement in sensitivity using a Polyimide backing patch to increase the separation between the neutral axis of the cantilever and the FBG [4]. Sensitivity ~450 pm/g, which was twice compared to conventional cantilever-mass design, was achieved for a specific cantilever-mass arrangement with a patch of thickness 150 $\mu m$.

The limit up to which the sensitivity could be increased by this mechanism is an important question and has been dealt with in this paper. In this paper the primary objective was to study the influence of patch thickness and also the Young's modulus of the patch material on the sensitivity of the FBG-accelerometer, by numerical simulations using COMSOL Multiphysics (version-4.2a) finite element analysis software. It has been shown that for a specific patch material, i.e. having the elastic modulus remaining same there is an optimum thickness of the patch for which the strain enhancement of a particular cantilever mass architecture becomes maximum and thus the sensitivity. Sensitivity of the order of 1062 pm/g has been measured for a particular configuration with a 1000 $\mu m$ teflon patch.

## 2. Theoretical Background

The architecture of the proposed accelerometer is illustrated in **figure1**. The strain experienced by the FBG from [4] and the cross-references thereof, may be expressed as,

$$\varepsilon_F(x) = \frac{3(0.5d + d_f)(L-x)}{(\omega_0^2 - \omega^2)L^3}.a \qquad (1)$$

where $d_f$ is the distance of the FBG from the surface.

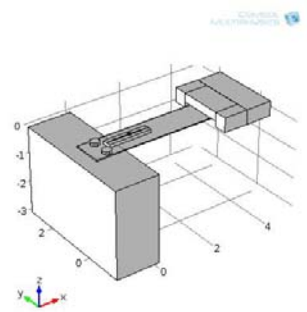

**Figure 1**. FBG-accelerometer geometry

The strain experienced by the FBG w.r.t. the strain at the surface of the cantilever $\varepsilon_S(x)$ can therefore be expressed as

$$\varepsilon_F(x) = \frac{(0.5d + d_f)}{0.5d}\varepsilon_s(x) \qquad (2)$$

The accelerometer sensitivity (wavelength shift of FBG per unit acceleration) is given by

$$S = \frac{\Delta\lambda}{a} = \frac{1.2 \times \varepsilon_F(x)}{a} \qquad (3)$$

where $\Delta\lambda$ is the FBG wavelength shift. The factor 1.2 is due to the fact that the strain sensitivity for FBGs with peak wavelengths in the C band regime, is about 1.2 $pm/\mu\varepsilon$ in general.

From eqns. (2-3), it is evident that larger the distance of the FBG from the surface, higher is the sensitivity. The term $(\omega_0^2 - \omega^2)$ in the denominator of the expression for $\varepsilon_F(x)$ indicates a frequency dependence of the accelerometer sensitivity which is usual for a vibrating cantilever system [5]. The sensitivity is nearly constant for frequencies much less than the resonance frequency. It gradually increases up to resonance and falls abruptly at frequencies beyond that. Based on the fact, in practice, the feasible frequency range of operation of this class of accelerometer is in general up to half the resonance frequency to avoid large sensitivity variation.

For a fiber of radius $r$, directly mounted on the surface,

$$\varepsilon_{FS}(x) = \frac{(0.5d + r)}{0.5d}\varepsilon_s(x) \qquad (4)$$

For a fiber of radius $r$, mounted on a patch of thickness $p$,

$$\varepsilon_{FP}(x) = \frac{(0.5d + r + p)}{0.5d}\varepsilon_s(x) \qquad (5)$$

Thus ratio of the strain experienced by the FBG mounted on a patch to the directly mounted FBG (the enhancement factor) may be represented as

$$IF = \frac{\varepsilon_{FP}(x)}{\varepsilon_{FS}(x)} = \frac{(0.5d + r + p)}{(0.5d + r)} \qquad (6)$$

In [4] eqn.(6) was used to predict the strain enhancement factor which clearly has a linear dependence with patch thickness and experimenting with a 150 µm patch we could get enhancement factor IF as predicted by eqn.(6). It may be noted that both the constituent terms $\varepsilon_{FP}(x)$ and $\varepsilon_{FS}(x)$ of eqn.(6) are dependent on the strain distribution $\varepsilon_s(x)$ on the surface of the cantilever. Now if the surface strain is assumed to be constant even though it is loaded with a patch of thickness *p* then eqn. (6) is sufficient to predict the enhancement factor but would not be so simple if the surface strain happens to change due to the modification of the cantilever by adding a part in the form of a patch. In that circumstance it is then required to numerically analyze the strain variation at the cantilever surface for this added structure to quantify its influence on the overall sensitivity enhancement. This in fact, as mentioned earlier forms the basis of the present paper and is elaborated in the subsequent sections.

## 3. Model using COMSOL Multiphysics

The geometry in **figure1** was analyzed using numerical simulations with COMSOL Multiphysics (version 4.2a) Finite Element Modeling software. The geometry comprised of a 40mm x 10mm x 0.32mm stainless steel

(SS316) cantilever mounted on a fixed aluminum block, a 15gm stainless steel inert mass attached at the cantilever tip, a 15mm x 3mm patch fixed on the cantilever and a polyimide coated silica fiber with diameter 150 $\mu m$, hosting the FBG sensor of length 4mm, was mounted on the patch. It is considered that the center of the FBG sensor is at 5 mm from the fixed point of the cantilever. It is assumed that a 10 $\mu m$ thick layer of adhesive connects the cantilever and the patch. A zoomed view of the patch mounted on the cantilever with adhesive and a fiber attached on it with the adhesive is shown in **figure 2**. The material properties were described using the database available in goodfellow.

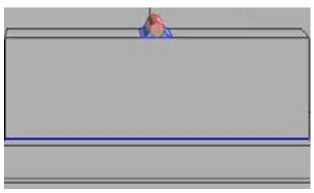

**Figure 2**. Zoomed cross-section of the FBG-accelerometer.

The Solid Mechanics Physics interface was used and a Linear Elastic Material Model was assumed for a Frequency Domain study. The equations governing the Frequency Domain study were

$$\left.\begin{array}{l} -\rho\omega^2\hat{u} - \nabla.\hat{\sigma} = \hat{F}v, \quad \hat{\sigma} = \hat{s} \\ \hat{s} - \hat{S}_0 = \hat{C} : (\varepsilon - \varepsilon_0 - \varepsilon_{inel}) \\ \varepsilon = \frac{1}{2}[(\nabla\hat{u})^T + \nabla\hat{u}] \end{array}\right\} \quad (7)$$

where $\hat{u} = \begin{bmatrix} u \\ v \\ w \end{bmatrix}$ is the displacement in the three directions, $\hat{s}$ is the stress tensor, $\varepsilon$ is the total strain tensor, $\hat{F}$ is the force, $\omega$ is the angular frequency and $\rho$ is the density.

The mount and the screws were assigned fixed constraint, the remaining domains and boundaries being free. Body loads for the cantilever, patch and the inert mass were applied in the negative z direction. The initial displacement values were zero.

A physics-controlled normal mesh comprising of 20438 free-tetrahedral elements was generated by the software (**figure 3**).

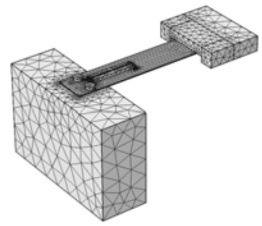

**Figure 3**. Mesh of the FBG-accelerometer.

The cantilever dimensions were chosen so as to have a low frequency, low ‘g’ accelerometer. The effect of the patch material properties and the patch thickness on the strain enhancement and resonance frequency were studied.

## 4. Simulation Results

### 4.1 Effect of variation of patch thickness on strain enhancement

The above geometry was analyzed for the three patch materials teflon, polyimide and aluminum. Teflon and polyimide have very low Young’s modulus compared to steel and are widely used as backing patch for mounting FBG sensors. Aluminum patch was also taken into consideration in our study to comprehend the specific case where the Young’s modulus of the patch is appreciably high as compared to that of the materials generally used as a backing patch like teflon or polyimide. The patch thickness was varied upto 2200 $\mu m$. The excitation frequency was scanned upto 10Hz and excitation amplitude was fixed at 1g(0-p). Assuming that the FBG is located 5mm from the cantilever pivot, the strain experienced by the FBG in $\mu\varepsilon$ is plotted against varying patch thickness at excitation frequency 10Hz for the three different patch materials e.g. teflon, polyimide and aluminum in **figure 4**. It is interesting to observe that the strain experienced by the FBG increases with the increase of the patch thickness up to a certain extent and then decreases with further increase of the patch thickness. It may also be observed that both sensitivity and maximum allowable patch thickness are inversely related with the Young’s modulus of the patch material. The values considered are 0.5GPa, 2.5GPa and 70GPa for teflon, polyimide and aluminum respectively.

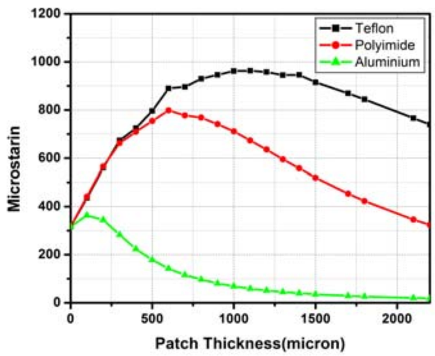


**Figure 4**. Simulated strain experienced by FBG on teflon, polyimide and aluminum patch for 10Hz excitation frequency and 1g (0-p) amplitude.

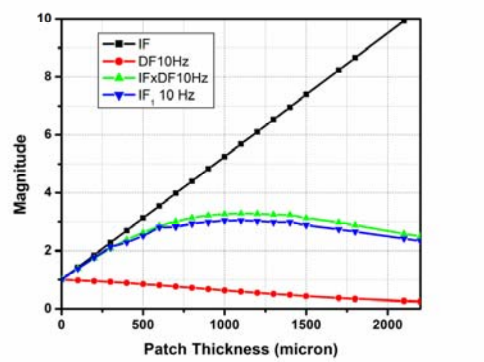


**Figure 5.** Simulated plot of enhancement factor without the effect of surface strain IF, decrement factor DF, IF x DF and enhancement factor with the effect of surface strain $IF_1$ at 10Hz.

For a teflon patch, the maximum strain as experienced by the FBG is 963 $\mu\varepsilon$ at 10 Hz which corresponds to a wavelength shift of ~ 1156 pm (considering 1.2 pm/ $\mu\varepsilon$ wavelength shift) when the patch thickness is 1100 $\mu m$. With a polyimide patch the maximum strain achieved at 10Hz is 798 $\mu\varepsilon$ for a patch thickness of 600 $\mu m$, while that with aluminum it is 364 $\mu\varepsilon$ for 100 $\mu m$ patch thickness. For this architecture the strain experienced by an FBG when mounted directly on the cantilever has been found to be 317 $\mu\varepsilon$ at 10Hz. Now as the strain experienced by the FBG as a function of the patch thickness for different patch material and also the same without any patch has already been computed, it is straightforward to obtain the enhancement factors (say $IF_1$) for individual cases by taking the ratio of the two quantities. It is thus apparent that the variation of the enhancement factor as a function of the patch thickness will be similar in nature to those as depicted in figures 3-5 and only the amplitude will be reduced by a constant factor. Which means the sensitivity enhancement factor will increase with the increasing thickness of the patch up to a certain point and beyond that will gradually decrease with further increase in the patch thickness. The result can be interpreted using **figure 5**. We have computed the surface strain $\varepsilon_s(x)$ [for x=5mm] as a function of the patch thickness (figure 5 is for a teflon patch) for different excitation frequencies with 1g (0-peak) excitation amplitude and a particular case for 10 Hz is shown by the solid dots in the figure.

It is found that the surface strain of the cantilever decreases linearly with patch thickness and may be seen as a decrement factor say DF. The enhancement factor IF as a function of patch thickness using eqn. (6), where the effect of surface strain was not considered explicitly, is shown by the solid squares in the same figure 6. The product of IF and DF is shown by the solid triangle which closely matches with the computed enhancement factor $IF_1$ for this particular case as explained in the previous paragraph and is shown by the inverted triangles. Thus the two factors IF and DF contribute to practical $IF_1$ i.e. their product has a maxima at a particular patch thickness and the effective strain on the patch beyond a certain thickness decreases. However, it may be observed that this effect is not predominant up to ~250 $\mu m$ patch thickness. As a result the plots for $IF_1$ and IF are close to each other up to this thickness and is almost linear as obtained in [4], where a 150 $\mu m$ polyimide patch was used.

### 4.2 Strain distribution along the fiber and optimal FBG location

In a basic cantilever based accelerometer where FBG is used to measure the bend induced surface strain the FBG is in general glued near to the fixed point of the cantilever to maximize the sensitivity within the permissible range. In general for a rectangular cantilever the surface strain linearly decreases along the length of the cantilever from the fixed point to the tip.

Therefore, apparently it seems that the sensitivity of the FBG will also have linear dependence with respect to its location along the length of the cantilever. However, while corroborating experimental results with the prediction it has been observed that the aspect requires a more careful study to identify the best FBG location for maximum strain sensing. In practice a length of ~10-12 mm fiber is glued on the cantilever surface for this purpose which hosts the FBG of length ~ 4-5 mm at some location along its length. Strain distribution along the fiber when glued on top of a patch has been computed for varying length of the fiber. One result for a 12 mm fiber sitting on a teflon patch of thickness 500 µm and 1000 µm has been shown in **figure 6**. The strain distribution related with the bending of the cantilever due to vibration for a 10Hz, 1g (0-p) sinusoidal excitation signal has been shown in the figure. The strain distribution was found to be parabolic in nature with a maximum at some point from the fixed point and also over a few millimeter the strain is almost uniform. Hence care must be taken to localize the FBG as close to the maximum strain location as possible. Any deviation from this location may cause a decrease in sensitivity i.e. a reduced strain induced wavelength shift. Also significant chirp may be generated along a long length FBG due to the non-uniform strain distribution along the FBG. Use of a small length FBG would alleviate the problem.

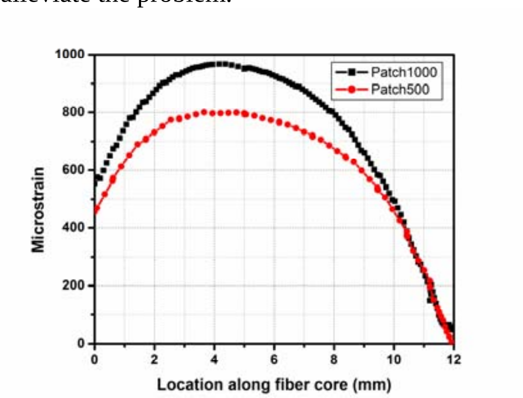


**Figure 6.** Simulated Strain along the fiber core for a teflon patch of 500 $\mu m$ and 1000 $\mu m$ for 1g (0-p) excitation amplitude at 10Hz.

Simulations with Optiwave for a 4mm long FBG show that this variation of strain as found in the present case along the FBG is equivalent to a chirp of ~.01nm and this amount of chirp does not degrade the spectral characteristics of the FBG.

## 5. Conclusions and Future Scope

To the best of our knowledge this is for the first time a detailed finite element analysis to understand a practicable concept of using a backing patch to enhance the sensitivity of the cantilever-mass based FBG accelerometer has been reported. The work thoroughly explored the influence of patch material (Young's modulus) and patch thicknesses on the strain transfer to the FBG sensor. In agreement with the numerical analysis, sensitivity ~1062 pm/g has been experimentally achieved with a particular accelerometer configuration with 1000 $\mu m$ teflon patch. This value is about 3 times as compared to a similar FBG-accelerometer without patch.

The effect of the patch material and the patch thickness on the vibration characteristics of the FBG accelerometer also requires a through investigation and is of our future target. Further experiments with different patch thicknesses and at different excitation frequencies will be carried out to corroborate the simulation results. The complete numerical analysis and the experimental results will be presented in our forthcoming paper.

## 6. References

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## 8. Acknowledgements

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