BRAGG GRATING CORROSION SENSOR

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INTRODUCTION

Historically, corrosion has not been included in the calculation of the life expectancy of aircraft. It is well known how stress-corrosion cracking and corrosion fatigue can significantly reduce the life expectancy of structures. Therefore, it can be correctly assumed that some aircraft flying near their expected life might actually be flying well beyond their “safe life”. Furthermore, due to DoD present tight budget requirements, its is expected that some defense aircraft might not be retired at their original expected life but will be reconditioned to fly beyond that time. All of these considerations indicate that early detection, quantification and prevention of corrosion is of critical importance for military aircraft. This is particularly true for Navy aircraft which fly in the most corrosive environment of all services.

A large number of fiber optic sensors [1, 2, 3] are being developed for various applications in different industry sectors such as the materials industry [4, 5] (smart processing, curing monitoring), automotive industry (pressure monitoring, oxygen content, highway axle count), health industry (catheter pressures), telecommunication industry (mirrors [6], modulators), and in the aerospace industry. The wide variety of uses that these sensor have is related to some of their unique properties such as small size, light weight, immunity to EMI, corrosion resistance and information carrying capacity. Most of these sensors use the same line for activation as well as for signal carrier. Some of these sensors allow for several of them to be place and accessed in a single line [7]. These sensors include the intrinsic/extrinsic Fabry Perot [8,9], intrinsic Bragg grating [10], line discontinuity and cladding sensor.

In this paper we describe how to make a Bragg grating corrosion sensor. There are several questions that have to be answered in order to effectively fabricate a Bragg grating corrosion sensor. Some of these questions are; What must the Bragg angle and period ($\theta_b$...
Fig. 1. Basic parameters are used in the model.

and \( \Lambda_B \) be in order to effectively scatter radiation out of the fiber at a desired scattering angle \( \theta \), what is the band pass of the scattered radiation for a given \( \theta_B \) and \( \Lambda_B \)? (this information is important in order to determine how many sensors can be placed in a single fiber, how will the scattered radiation measure the state of corrosion of the surrounding environment and finally how will the information be collected back into the fiber?

In section II the Tapped Bragg Grating (TBG) fabrication parameters are described. In section III the band pass of the TBG is calculated for two different fiber modes. In section IV a corrosion sensitive chemical sensor is described as well as a possible mechanism for collection of the radiation back into the fiber. Finally in section V the summary and conclusions are given.

**TBG FABRICATION PARAMETERS**

In order to answer the first two questions addressed in the introduction, the induced current approximation [11] will be used to model the effects of a TBG in an optical fiber. In the induced current approximation, radiation fields produced by perturbations to the index of refraction of the core of optical fibers are assumed to originate from induced currents in the fiber. These currents take the for

\[
J = \frac{\varepsilon_0}{\mu_0} \frac{1}{2} k \cdot (n_0^2 - n^2) \cdot E
\]

where \( n_0^2 - n^2 \) is the square of the differences of the perturbed to unperturbed index of refraction, \( E \) is the unperturbed electric field inside the core of the fiber and \( k \) is the wave

\[
E = -\frac{J_1(U \cdot r')}{J_1(U)} e_\theta
\]

\[
E_r \propto -\frac{a_1 J_{\nu-1}(U \cdot r') + a_2 J_{\nu+1}(U \cdot r')}{R J_\nu(U)} f_\nu(\phi')
\]

\[
E_\phi \propto -\frac{a_1 J_{\nu-1}(U \cdot r') - a_2 J_{\nu+1}(U \cdot r')}{R J_\nu(U)} g_\nu(\phi')
\]
number. The quantity $n_0^2 - n^2$ has been modeled by

$$n_0^2 - n^2 = 2n_0 \Delta n \cdot \cos(\vec{K}_B \cdot \vec{r}')$$  \hfill (4)

where $\Delta n$ is the difference in the index of refraction of the perturbed to unperturbed regions in the fiber core. The argument of the cosine is the product of the Bragg wave number ($K_B = 2\pi / \Lambda_B$) times the position vector. Figure 1 shows a schematic representation of the parameters used in this model. The electric field in Eq. 1 is given by Eq. 2 for transverse field modes and by Eq. 3 for hybrid field modes (The z-component is not shown because it produces a vanishing contribution in the weak field approximation). The parameter $R$, $a$, $f_v$ and $g_v$ are defined in reference 11. The radiation fields can now be calculated using standard antenna theory, that is, by calculating the vector potential

$$A = \frac{\mu_0}{4\pi s} \cdot e^{ikn_0s} \cdot \int_{V'} \mathbf{J}(r', \phi', z') \cdot e^{-ik\cos(\chi')} \cdot dV'$$ \hfill (5)

where $s$ indicates the scattering direction and

$$s' \cdot \cos(\chi') = r' \sin(\theta) \cdot \cos(\phi - \phi') + z' \cos(\theta)$$ \hfill (6)

where the primed coordinates refer to a “cylindrical” coordinate system inside the core of the fiber, while the unprimed coordinates refer to a “spherical” coordinate system describing the scattered fields. Fig. 2 shows the relationship between all coordinates.

By integrating Eq. 5 on the variable $z'$, the Bragg condition (Eq. 7) is directly obtained. This condition is simply a statement of the conservation of the linear momentum along the $z$ direction.

$$\beta - kn_z \cos(\theta) = K_B \sin(\theta_B)$$ \hfill (7)

where the parameter $\beta$ is the propagation constant of the mode traveling down the fiber, $k$ is the wave number in vacuum of the EM field injected into the fiber and $n_z$ the index of refraction of the cladding. Fig. 1 gives a representation of the main parameters describing a tap Bragg Grating.

Fig. 2: Scattering coordinate system.
For a given electromagnetic mode $\beta$ propagating down the core of a fiber and for a given desired scatter angle $\theta$, many combinations of $K_\beta$ and $\theta_\beta$ exist that satisfy Eq. 7. It is obvious that a second condition is required in order to completely specify the Bragg parameters for a given mode and scatter angle. The second equation can be obtained by finding the values of $K_\beta$ and $\theta_\beta$ that produce maximum amount of scattered radiation for a given mode $\beta$ in a specified scattering direction $\theta$. This can be done by integrating Eq. 5 over the variables $\phi'$ and $r'$. The integrals are not trivial, but it can be shown that for any fiber mode there is a common prefactor which is shown in Eq. 8

$$A(\theta,\phi) \propto \frac{1}{(U(\beta))^2} \cdot F(\theta,\phi) \cdot \delta(\beta - n_\text{cl} \cos(\theta) - K_\beta \sin(\theta_\beta))$$  \hspace{1cm} (8)$$

Where the parameter $U(\beta)$ is defined in Ref. 11 and where

$$P(\theta,\phi) = \left( K_\beta^2 \cos^2(\theta_\beta) + k^2 n_\text{cl}^2 \sin^2(\theta) - 2 K_\beta n_\text{cl} \sin(\theta) \cos(\theta_\beta) \cos(\phi) \right)^{1/2}$$  \hspace{1cm} (9)$$

From Eq. 8, it can be seen that the vector potential $A$ (and therefore the Poynting vector) has a maximum when $A(\theta=0) = U(\beta)/R$. This gives the second condition for the fabrication of a tapped Bragg grating

$$n_\text{cl} \sin(\theta) = K_\beta \cos(\theta_\beta) \pm \frac{U(\beta)}{R}$$  \hspace{1cm} (10)$$

Eqs. 7 and 10 completely specify the Bragg parameter $(K_\beta, \theta_\beta)$ when the propagation constant $\beta$ and the desired scattering angle $\theta$ are given. It can be shown that Eq. 10 is a statement of the conservation of momentum along a direction normal to the fiber and in the plane containing the Bragg vector. Furthermore, when $U \to 0$ (weak guidance approximation), Eqs. 7 and 10 reduce to

$$K_\beta = 2 n_\text{cl} \sin(\theta / 2)$$  \hspace{1cm} (11)

$$\theta_\beta = \theta / 2$$
Fig. 3 shows what the Bragg period $\Lambda_B$ should be in order to achieve maximum amount of scattered radiation in a particular scattering direction $\theta$ ($\theta$ is measured relative to the fiber axes direction). The Bragg angle $\theta_B$ is simple half of the scatter angle as shown in Eq.11. This answers the first question that was addressed at the beginning of the section, i.e., What must the Bragg angle and period ($\theta_B$ and $\Lambda_B$) be in order to effectively scatter radiation out of the fiber at a desired scattering angle $\theta$.

**TBG BAND PASS**

One of the great advantages of Bragg gratings is that, due to the extreme spectral narrowness of the reflected component [12] (on the order of $\Delta \lambda = 0.1$ nm), many Bragg gratings can be placed in a single fiber with the ability of being able to interrogating each individual grating individually [7]. This can be done by fabricating each grating in the fiber with a different Bragg period $\Lambda_B$ and then interrogating the gratings with a broad band signal (BBS). If the spectral width of the BBS is $\Delta \lambda_{BBS} = 50$ nm, centered at $\lambda = 1300$ nm in a fiber of index $n = 1.4$ and the desired strains to measured are of the order of $\varepsilon = 100$ $\mu$strains, then the number of sensors that could be addressed would be $N = \Delta \lambda_{BBS} / (2n\lambda\varepsilon) = 50/3.6 = 13$ sensors. Notice that in this case the reflected spectral spread for the desired strain measurements is $\Delta \lambda_{spread} = 2n\lambda\varepsilon = 3.6$ nm which is much larger than the spectral width of the reflected signal $\Delta \lambda = 0.1$ nm.

In the case of a TBG the situation is different because now for a set of Bragg parameters ($K_B$ and $\theta_B$) there will be a broad range of propagation constants $\beta$ (and therefore wavelengths) that will satisfy Eq. 7 for different scattering angles. In the weak guidance approximation ($\beta \rightarrow kn_{cl}$) the expression for the spectral width ($\Delta \lambda$) in terms of the angular spread $\Delta \theta$ can be obtained by differentiation of Eq. 7

$$\Delta \lambda = \lambda \cdot \frac{\Delta \theta}{\tan \left( \frac{\theta}{2} \right)}$$  \hspace{1cm} (12)

The angular spread can be calculated by determining the angle at which Eq. 8 has its first zero. In the weak guidance approximation the function $F(\theta, \phi)$ in Eq. 8 can be shown to be proportional to $P \cdot R \cdot J_n(P \cdot R)$ therefore that equation can be written as shown in Eq. 13.

$$A(\theta, \phi) \propto \frac{J_n(P \cdot R)}{P \cdot R} \cdot \delta(K_B \cos(\theta_B) - 2kn_{cl} \sin(\theta))$$  \hspace{1cm} (13)

The zeros of the previous equation are the zeros of the $n$th order Bessel function. Therefore we get

$$P \cdot R = a_n$$

$$\sin(\theta) - \sin(\theta_{zero}) = \frac{a_n}{R \cdot k \cdot n_{cl}}$$  \hspace{1cm} (14)

where $a_n = 2.40, 3.83, 5.14, 6.38 \ldots$ for $n = 0, 1, 2, 3, \ldots$. 

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Fig. 4 shows the angular and spectral width for two different fiber modes and two different scattering angles as a function of the Rk product. From that graph it is clear that the larger the Rk product, the smaller the diffraction effects, and therefore the narrower the angular and spectral broadening. In contrast, the larger the Rk product is the more modes that the fiber will be able to sustain and therefore more intermodal coupling effects in the fiber. For single mode operation the Rk value has to be smaller than the \( 2.45/(n_{q}^{-2} - n_{q}^{2})^{1/2} \). For a typical 10 \( \mu \)m core fiber Rk has a value of 60. One can see from Fig. 4 that the spectral width is \( \Delta \lambda = 0.5 \) \( \mu \)m for light scattered out of the fiber at 90°. This is more than 3 orders of magnitude bigger than in the case of a Bragg grating. The TBG band pass can be made smaller by increasing the scattering angle as shown in Fig. 4. All these considerations will have to be taken into account when fabricating TBG sensors.

ELECTROCHEMICAL COMPONENT

An important component of a corrosion sensor is the chemical or electrochemical species that responds to changes in the environment surrounding the sensor that result from the corrosion process itself. This response can manifests itself as a change in any of the electrical, mechanical, optical or physical property of the chemical or electrochemical species. Various types of BG sensors can be fabricated [13], each one to optimally respond
to any of the specific property of interest [14]. In this work an electrochemical species has been studied that changes its absorption coefficient when in the presence of iron ions, which are the by product of the oxidation process in iron and steels.

Fig 5 left shows the transmission spectra of Ferroin (1,10 Phenanthroline) as a function of the concentration of iron ions. It can be seen that spectrum that small amounts of Iron ions in a solution of this type can substantially increase the absorption behavior of the solution. As a result of the redox reaction, a clear coloration change is observed in the solution varying from transparent to red. This strong sensitivity to iron ions can be used as an indicator of corrosion. By coating a TBG with this type of buffer layer and by surrounding it with a non-continuous metallic reflector (as shown in Fig. 5 right) to collect back the tapped radiation, a corrosion sensor could be fabricated. The amount of corrosion would be proportional to the decrease in intensity.

CONCLUSION

The basic equations required to design a TBG have been derived. After careful interpretation of these equations it was found that simple momentum conservation arguments could have been applied to derive them, even though momentum is only conserved along the fiber axes direction. It was found that the spectral width $\Delta \lambda$ for the TBG was orders of magnitude larger than for the case of a BG. This fact considerably limits the number of sensors that can be placed in an optical fiber without crosscoupling. Time domain reflectometry could conceptually be used to overcome this problem. Finally the absorption spectra of Ferroin was measured as a function of the amount of iron concentration. A strong absorption line appears at 520 nm. This change in the absorptivity of Ferroin was shown to be the base for a corrosion sensor.

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REFERENCES


