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# Application of Fe-C coated LPFG sensor for early stage corrosion monitoring of steel bar in RC structures

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## HIGHLIGHTS

- Fe-C coated LPFG was applied to monitor steel bar corrosion.
- Fe-C coated LPFG can monitor steel bar corrosion for 14 h in NaCl solution.
- Fe-C coated LPFG can monitor steel bar corrosion in mortar for 14 days.
- Fe-C coated LPFG demonstrate high sensitivity for steel corrosion loss measurement.

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## ABSTRACT

Fe-C coated long period fiber grating (LPFG) sensor was employed to monitor the corrosion-induced mass loss of steel bar in 3.5 wt% NaCl solution and steel bar in mortar cylinder. A two-stage process of the change in resonant wavelength as a function of the corrosion-induced mass loss of steel bar was observed. The LPFG sensor can effectively monitor steel bar corrosion loss in 3.5 wt% NaCl solution for 14 h with a sensitivity of 0.124 mg/nm change of the resonant wavelength, and in mortar cylinder for 14 days with a sensitivity of 0.405 mg/nm change of the resonant wavelength, respectively.



## 1. Introduction

Reinforcement steel corrosion is one of the main causes of reinforced concrete (RC) deterioration. It is estimated that, in the U.S. alone, the annual corrosion-induced direct maintenance and capital cost of concrete highway bridges was around $4.0 billion in 2002, including $2 billion for concrete bridge decks and $2 billion for concrete sub- and superstructures [1]. The indirect cost of corrosion due to traffic delay and lost productivity was estimated to be as high as 10 times that of direct corrosion cost [1]. Chloride from de-icing salt or marine environments, carbon dioxide in the atmosphere, and other aggressive chemicals penetrate through the concrete cover and break down the passive film formed on the surface of steel reinforcement, resulting in corrosion initiation [2,3]. Over time, corrosion develops and propagates, causing concrete cover cracking, reduction of cross-sectional area of steel bars, bond degradation between steel reinforcement and surrounding concrete, and decrease of carrying capacity of RC structures [4–7].

Over the past decades, many techniques or methods have been proposed and developed to monitor reinforcement steel corrosion in concrete structures. As chloride and carbon dioxide are the two primary aggressive species that initiate steel bar corrosion in RC structures, their penetration through concrete cover can be monitored and used as an index for corrosion evaluation [8–11]. However, there is no direct relationship between the concentration of chloride or pH values of the concrete and the corrosion rate of steel reinforcement, which makes it impossible for precise and long-term corrosion monitoring. Sensors to monitor oxygen concentration [12] and moisture [13] were also studied to evaluate reinforcement steel corrosion in RC structures.

Steel corrosion in nature is an electrochemical process, thus electrochemical methods have particular advantages over other techniques. The widely used electrochemical techniques for steel corrosion measurement include half-cell potential, linear polariza-

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tion resistance, electrochemical impedance spectroscopy, electrochemical noise and transient techniques such as galvanostatic or potentiostatic pulses. Embedded potential sensor based on $MnO_2$ was characterized in concrete, and electrochemical corrosion tests showed that it could be used for corrosion monitoring of steel in concrete [14]. This $MnO_2$ potential sensor was assembled with corrosion rate monitoring probe sensor to evaluate active and passive condition of steel reinforcements in RC structures [15]. Later, $Mn_3O_4$ based pellet electrode was fabricated and characterized for corrosion assessment of steel rebar in high alkaline medium through electrochemical methods, and results exhibited better characteristics suitable for high alkaline concrete environment and differentiated the passive and active status of steel rebar [16]. Metal-metal oxide (MMO), graphite and laboratory-made Ag/AgCl electrodes were also electrochemically characterized to be used as reference electrode for corrosion monitoring of steel in RC structures [17]. $NiFe_2O_4$ film was applied to assemble a solid-state reference electrode and characterization results showed that this electrode could be used as a reference electrode for the corrosion monitoring of RC structures [18]. To give more comprehensive evaluation, integrated sensor systems were proposed, which provided measurements of open circuit potential, corrosion rate, concrete resistivity, oxygen and chloride contents, temperatures and pH values of concrete [19,20]. In addition to these electrochemical methods, steel corrosion in concrete can be monitored indirectly through the change of some physical properties such as corrosion products expansion, concrete cover cracking, and corrosion-induced stiffness reduction of RC structural members by using piezoelectric transducers [21], acoustic emission [22,23] and impact-echo stress pulse [24].

Use of optical fiber sensors to monitor steel corrosion has attracted a lot of interests over the past two decades due to its small size, high precision and stability, electrically passive operation, electromagnetic immunity, possibility of being inserted in large sensor networks and adopting multiplexing configurations [25]. By coating a thin layer of Fe-C film on the core surface [26], or pure iron film on the cleaved end of a fiber [27,28], or a polyurethane coating containing nano-iron (~54 nm)/silicate particles (~15 nm) on the cladding surface [29], the steel bar corrosion can be monitored by observing the change in the reflected or transmitted light spectrum. The corrosion also can be monitored indirectly by measuring the corrosion-induced deformation of optical fiber due to corrosion products expansion [30], because the volume of corrosion products is usually 3–7 times greater than the steel it consumes.

Long period fiber grating (LPFG) is a periodic modulation of the refractive index of the core by ultraviolet, infrared or $CO_2$ laser irradiation, ion implantation, diffusion of dopants into the core, relaxation of mechanical stress, and electrical discharges [31]. It typically has a period in the range of 100 μm–1 mm. LPFG couples light propagating in the core code with light co-propagating in the cladding modes, resulting in a series of attenuation bands in the transmitted spectrum as shown in Fig. 1a. The central wavelength corresponding to the maximum transmission intensity loss is the resonant wavelength, which is expressed as [32]:

$$\lambda_{res} = (n_{co}^{eff} - n_{cl,m}^{eff})\Lambda \quad (1)$$

where $\lambda_{res}$ is the resonant wavelength, $\Lambda$ is the grating period, $n_{co}^{eff}$ and $n_{cl,m}^{eff}$ are the effective refractive indices of the fundamental core mode and the $m$-th cladding mode, respectively. The term $n_{cl,m}^{eff}$ is a function of refractive indices of the core ($n_1$) and cladding ($n_2$) of the fiber as well as its surrounding medium ($n_0$).

In our previous studies, Fe-C coated LPFG corrosion sensors were proposed [32] and the corrosion mechanism and sensitivity were characterized in 3.5 wt% NaCl solution [33]. The LPFG corrosion sensor consists of an inner layer of silver and an outer layer of Fe-C film as shown in Fig. 1a. The Fe-C coating was electroplated and energy-dispersive X-ray spectroscopy (EDS) analysis showed a chemical composition 1.13 wt% C, 14.48 wt% O, with the balance Fe [33]. When the outer Fe-C film corrodes, the effective refractive index of the surrounding medium changes from $n_0$ to $n_0'$, resulting in a shift of the resonant wavelength from $\lambda_{res}$ to $\lambda_{res}'$ in the transmitted spectrum as indicated in Fig. 1b, which in turn was used for corrosion monitoring.

However, its application to monitor corrosion of steel bars has not been investigated yet. To successfully use this LPFG sensor for corrosion monitoring of reinforcement steel in RC structures, a relationship between the corrosion-induced mass loss of steel bar and the change in the resonant wavelength of Fe-C coated LPFG corrosion sensor needs to be established. In this study, the Fe-C coated LPFG corrosion sensors are employed to monitor steel bar

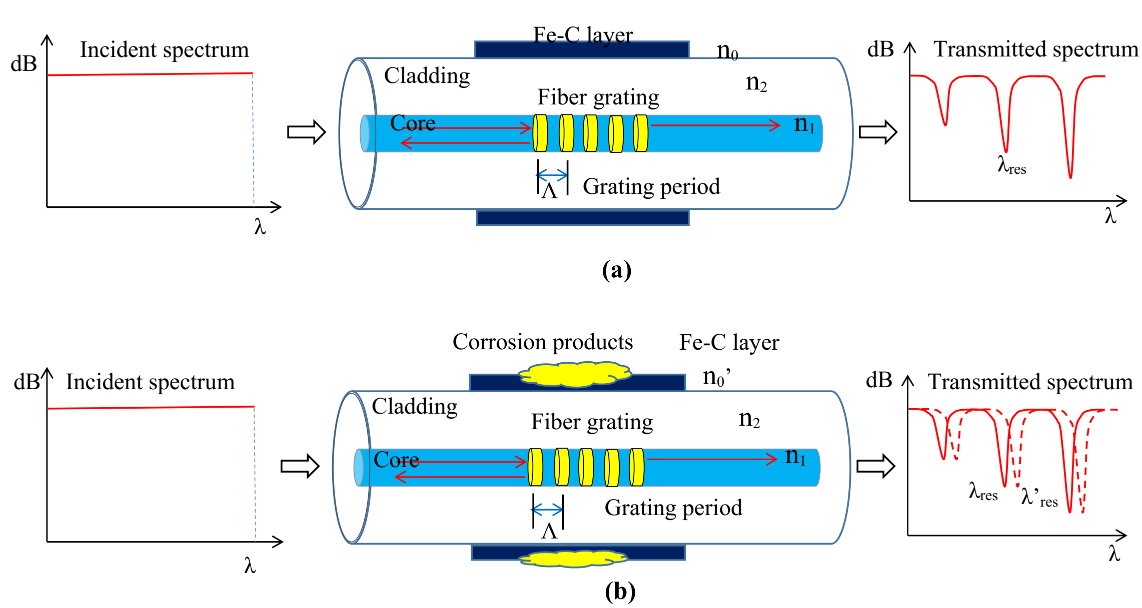


**Fig. 1.** Schematic illustration of corrosion sensing mechanism of Fe-C coated LPFG (a) before corrosion of Fe-C layer, and (b) after corrosion of Fe-C layer.