Development of metallized three-directional fibre Bragg grating strain sensor

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Abstract. The theory and application of fiber Bragg grating sensors are studied in this paper. The three-directional metallized fiber Bragg grating strain sensor with temperature compensation has been developed. The Metallization Technology of fiber grating is studied. The Metallization Technology Scheme of fiber grating is discussed in detail. The electroless composite nickel-plating process and the formula of nickel-plating process are given. A metal fiber grating strain sensor with temperature compensation is developed. The metal fiber grating sensor is fixed to the substrate by laser welding, and a one-way metal fiber grating strain sensor with temperature compensation is formed. Three unidirectional metallized fiber Bragg grating strain sensors are connected with the developed common welding blocks to form a three-directional strain flower. Comparing with resistance strain rosette stress test and its application in ship structure stress monitoring, the fiber grating strain sensor developed in this paper fully meets the requirements of large-scale structure long-term strain monitoring.

1. Introduction

In the structure healthy monitor area, the fiber-optic raster sensor has many advantages in anti-electromagnetic disturbance, lightweight, longer working life and better electric insulation, etc., but at the same time, the fiber-optic raster sensor also has some natural defects, for example, the fiber-optic raster self-utilized strain range only 3000με(±1500με), and the fiber-optic raster cross affected by the temperature and restrain, need process temperature to compensate when only use it to do restrain measure. These two defects seriously restricted the application of fiber-optic raster sensor in ship use structure monitor system. In order to solve the problems of small volume and small constraint range, the complex design of elastic element structure is generally used to reduce the sensitivity. But this complex structure exists two problems, the first is that the linear ratio comes to be bad after restraining pass through multiple times transmit, the second is that the complex structure increased the size of the sensor invisibly, and make it unable to install at some narrow empty points. The three-directional sensors are more sensitive, because the area adopts three-directional sensors monitor generally are in complex structure and space are narrower, so it asked the sensor size as small as possible. At the same time, if adopt common adhesive seal packing the fiber-optic raster sensor and reduce the sensitivity mechanism, this will be caused bad temperature linear, because it affected by the heat expansion coefficient of adhesive, and finally caused compensate result incorrectly.

Herein, according to the above fiber-optic raster sensor research and manufacture existing problems and application characteristics of three-directional sensor, this article researched and designed a simple structure, smaller size, easy and flexible installation three direction metallization seal packing fiber-
optic raster restrain sensor, through simulation calculating and imitate verification. This sensor has bigger measure range, high precision and better stability, it already applied in the solid ship structure healthy monitor. The result shown that this sensor completely meets the ship test requirements [1, 2].

2. Technical principle

The Fiber-optic Bragg raster is the most common fiber-optic raster, it’s raster period and refractive index modulate depth (also called effective refractive index) all are constant, the raster wave vector direction is unanimous with the fiber-optic axial. It is one excellent performance narrow band reflex filtering non source element. The raster wave vector which meet Bragg raster wave length condition will be reflex back when fiber-optic transmission pass through fiber-optic Bragg raster, then the incidence raster wave vector will be divided into two parts: penetrance raster wave vector and reflex raster wave vector. This is the basic working principle of fiber-optic Bragg raster. This characteristic of fiber-optic Bragg raster based on the period distribution of raster refractive index, but this period refractive index distribution comes from the raster specially write-in process technology, means utilize the outer energy change the refractive index on the naked fiber-optic. Currently the existed Bragg raster write-in technology have: phase masking technology, amplitude masking technology, point to point write-in technology, holographic write-in technology and online write-in technology, etc., widely applied in these technologies are phase masking technology. Then centre wave length which meet fibre-optic Bragg raster is:

$$\lambda_B = 2\textit{neff} \Lambda$$

In the formula, $\lambda_B$ is the fibre-core base mould coupling resonance oscillation wave length of fibre-optic Bragg raster; $\textit{neff}$ is the effective refractive index of fibre-core conduct mould; $\Lambda$ is fibre-optic raster period. The formula (1) is the base of research and develop the fiber-optic Bragg raster sensor. Any physical quantity which can change the raster effective refractive index or raster period all can change the centre wave length of raster. The strain (or stress) and temperature mostly able to directly change the physical quantity of Bragg raster wave length obviously. The raster period will happen change when the Bragg raster under action of outer strain (or stress), at the same time, the light elasticity effect will be caused raster effective refractive index changed. Currently existing various sensors which based on fiber-optic Bragg raster almost are directly or indirectly utilize strain or temperature to change the raster centre wave length, achieved the purpose that test the need be tested physical quantity [3].

3. The metallization technology of fiber-optic raster

The technology process of chemical nickel plating on quartz fiber-optic surface same to other non-metal surface: firstly, all need process handle before plating on the base body surface, and make it to be catalyse surface with chemical plating performance, then chemical plating on the base body surface. Need further more process inspection to judge the effect of chemical nickel plating of each item performance of its surface nickel plating layer after plated the nickel-plating layer on the quartz fiber-optic surface. Generally, non-metal no electric conduct performance, especially no catalyse activity in the chemical nickel plating, so if need obtain the chemical nickel-plating layer which with better combining force with non-metal base body then need process better pre-treatment before plating on the surface of these materials [4]. The detail fiber-optic raster metallization technology process as below.

First step: remove coating layer. The common quartz fiber-optic formed with fiber-core, cladding and organic coating layer. Thereinto, the fiber-core finish the light signal transmission, the cladding seal the light in the fiber-core, protect the fiber-core and strengthen the mechanical strength of fiber-optic, the materials of these two parts are quartz glass, but the refractive index of fiber-core bigger than refractive index of cladding, then finish the complete reflex process of light transmission through this. The total diameter of fiber-core and cladding about 12μm, very easy to be broken, so the surface coating is organic coating layer like polyurethane, epoxy resin and silicone resin with about 62.5μm thickness. But more bad combine force among coating layer and cladding, this affect the transmit sense effect of fiber-optic raster and the coating layer can’t withstand the application temperature in seal packing and high temperature, should remove it before handle. So, the chemical nickel plating on quartz fiber-optic
surface means the chemical nickel-plating process on the cladding surface. This coating layer in the experiment in this article need use blade manually removed; then use concentrated sulfuric acid soaked about 10 minutes to remove the organic remain layer.

Second step: surface clean. Use the dust free paper which wet by the absolute ethyl alcohol carefully wipe several times after removed the coating layer, make ensure the naked fiber surface cleaned. Then use deionized water washing several times, wash off the absolute ethyl alcohol which absorbed on the naked fiber surface. If the naked fiber surface absorbed absolute ethyl alcohol then very small absorb glue body palladium capacity at where has absolute ethyl alcohol when glue soaking glue body palladium, even though can’t absorb it. The washed naked fiber should use the dry dust free paper wipe clean rapidly, and soak into glue body palladium solution immediately, prevent polluted.

Third step: coarsening. The purpose of coarsening is strengthened the combine strength between fiber-optic base body and plating layer, the coarsening also divided into mechanical coarsening and chemical coarsening, here adopt chemical coarsening. The chemical method is utilized the corrosive acid and alkali corrode the base body surface, make the base body surface come to be microcosmic roughness, make the surface has hydrophily characteristic, not only can be wet by water, but also can improve the combine strength of plating layer and base body. Generally used the mixture solution of HF acid and other acid to process weaken corrosive, adopt the coarsening solution that volume ration of HF:H2SiF6: H2O at 1:1:1 to process coarsening. Big affection of coarsening to final plating layer, short coarsening time, no enough surface roughness and affect the combine force of plating layer, but too long coarsening time, easy to corrode the raster and affect its optic performance, so it’s better to adopt 20min at coarsening time.

Fourth step: soak glue body palladium. Before invent the glue body palladium, step to step activate method is the most traditional method which activate on the non-metal surface. Firstly use 5% stannous chloride water solution process sensitization handle, the sensitization is soaking in the solution with stannous chloride 40g/L and hydrochloric acid 100ml/L, not washing and directly soak into activate solution. Then use 2%~3.5% PdCl2 water solution to process activate handle again. The substance of activate is embed metal ion which has catalyze activity at hypophosphorus acid oxide and nickel ion deoxidize on the base body surface. This method simple operation and lower cost, but the sensitization liquid most easy to be oxide, not better catalyze effect, and too short storage time. Adopt glue body palladium solution to activate the quartz fiber-optic surface in the experiment. Completely dissolve 10g stannous chloride into 20ml concentrate hydrochloric acid. Additionally pick 0.3g palladium chloride dissolve into 10ml concentrate hydrochloric acid and 10ml distilled water, after stirring till completely dissolved, slowly add this liquid into the early stannous chloride solution with continue stirring. Then add compound well 200ml 1000g/L sodium chloride solution after mix stirring about 10 minutes, mixture stirring 10 minutes again. Finally fix volume to 1L after completely mixed, then can get the better salt base glue body palladium solution keep warm 3h under 60℃. Then can absorb one-layer glue body palladium pellets after soak the handle well fiber-optic in the glue body palladium solution 10 minutes.

Fifth step: release glue. The fiber-optic surface absorbed glue body palladium pellets no catalyze activity, need destroy the glue group structure through release glue, peel off the divalent tin ion around the palladium pellets, expose the metal palladium pellets with catalyze activity. Place the fiber-optic with absorbed glue body palladium into 0.25g/L palladium chloride solution 1 minute then can release glue.

Sixth step: chemical compound nickel plating (Ni-P-ZrO2). Configure solution according to the below recipe, place the handle well fiber-optic raster into the reaction liquid, and use water bath keep 2h, formed the 80 μm nickel layers on the fiber-optic surface finally. The technology in this article added ZrO2 micro pellets to increase anti grind and anti-corrode performance [5, 6] based on document [7]. The technology parameters of chemical compound nickel plating shown in table 1.

Seventh step: nickel electric plating. Soak the plated parts into the metal salt solution as negative pole, the metal nickel plate as positive pole, it will deposit the meal nickel plated layer on the plated parts after connect the DC power supply. Put the chemical nickel-plated fiber-optic into nickel plating
solution for nickel plating, can obtain different thickness nickel layer through adjust the electric plating time. The nickel plating (bright nickel) reference the recipe and configure method (shown in table 2):

| Table 1. Technology parameters of chemical compound nickel plating |  
| Parameter | Index  |
| NiSO\(_4\).6H\(_2\)O | 25g/L |
| NaH\(_2\)PO\(_2\).H\(_2\)O | 20g/L |
| C\(_3\)H\(_6\)O\(_2\) | 20mL/L |
| H\(_3\)BO\(_3\) | 20g/L |
| ZrO\(_2\) micro pellets | 10g/L |
| Temperature | 86°C |
| PH | 5.1 |
| Stirring strength | (20-30) times/hour |
| Nickle plating time | 2h |

| Table 2. The technology parameters of nickel electric plating |
| Parameter | Index  |
| NiSO\(_4\).6H\(_2\)O | 280 g/L |
| NiCl\(_2\)-6H\(_2\)O | 21g/L |
| H\(_3\)BO\(_3\) | 45g/L |
| Propoxybutylene glycol | 0.1g/L |
| Sodium dodecyl sulfate | 0.1g/L |
| Temperature | 57°C |
| PH | 4.2 |
| Current density(mA) | 2.5 |

Embed the sensor into metal base body, need a certain thickness metal protection plating layer. If plating layer too thin, it easy to make the sensor damaged during embed process, even though invalid, if too thick plating layer, not only add plating time, but also caused the stress transmit sense delay, increase the measure error. At the same time, the modulus elasticity of medium metal protect layer reflect the index of material resist the elasticity deformation capacity, represent the limit deformation capacity of protect layer [8], it has assignable influence at stress transmission.

4. Reduce The whole set seal packing of three direction fiber-optic raster sensor
Generally the reduce sensitivity in currently domestic and oversea strain sensor all are the method that utilize the polymer seal packing raster, or adopt mechanical structure realize reduce sensitivity, but the structure and technology all are more complex, only stay at the discussion of method, not propose one set practical reduce sensitivity action and method according to the engineering application requirements. This article will realize strain’s optimize distribution through change the mechanics characteristics of sensor’s perception part, and place the fiber-optic raster sensitive elements on the corresponding position, design the three direction FBG increase-reduce sensitive strain sensor. The strain sensor module include three ring reduce sensitive base sheet and the sensor welding blocks which connect both end of three ring reduce sensitive base sheet, raster seal packing on the concave groove of three ring reduce sensitive base sheet, parallel evenly distributed three ring structure on the concave groove of three ring reduce sensitive base sheet, the armored pipe fixed on the sensor welding blocks, sensor welding block welded on the waiting measure structure surface. Temperature compensate sensor module include temperature compensate base sheet and temperature compensate base plate which connect with one end of temperature compensate base sheet, temperature compensate base plate fixed on the sensor welding blocks, the concave groove in the temperature compensate base sheet place the metallization naked raster [9].

5. The whole set seal packing of three direction fiber-optic raster sensor
Currently the widest application of fiber-optic intelligent material structure is the intelligent composite material structure which use composite materials as base body, but, it’s very difficult to embed the fiber-optic sensor into the metal base body material, this is one bottle-neck which restrain development of fiber-optic intelligent metal structure.

5.1. The connection between fiber-optic raster and reduce sensitivity base
Because this article processed metallization seal packing at fiber-optic raster and make it can be welded, so we adopt laser welding method when connecting the fiber-optic raster and reduce sensitivity mechanism. The laser welding at quick welding speed, high precision and small remain stress.
5.2. The whole set seal packing
The connect method between reduce sensitivity base and welding blocks is activity connection, this method mainly meet curved surface installed. Three direction sensor formed with three mutual 45° reduce sensitivity mechanism and around one common welding block, another end of each reduce sensitivity mechanism connect with respective welding blocks, shown as Figure 1, the whole set covered by one protection cover, the Figure 2 is three direction fiber-optic raster strain sensor which welded on the ship.

![Figure 1. Three direction fiber-optic raster restrain sensor structure](image1.png)

![Figure 2. The actual product picture](image2.png)

6. Metering performance contrast experiment
This article adopts equal strength beam. Stick the FBG rosette age and electric resistance rosette age on the completely symmetrical up/down surface of equal strength beam according to a certain angle, process level VI loading on it, loading 5 times at each level and pick the average value, finally get the below contrast data (shown in table 3). The experiment result shown that this article referred three direction rosette age and common rosette age metering performance in the market at smaller error [10].

| Fiber | 0°  | 45° | 90° | Main strain | 0°  | 45° | 90° | Main strain | Main strain fractional error(%) |
|-------|-----|-----|-----|-------------|-----|-----|-----|-------------|-------------------------------|
| 121   | 96  | -12 | 132.886 | 124  | 98  | -11 | 135.737 | 2.145 |
| 483   | 398 | -48 | 538.545 | 490  | 402 | -47 | 545.031 | 1.2  |
| 983   | 808 | -97 | 1094.78 | 979  | 809 | -95 | 1092.43 | 0.215 |
| 1986  | 1636 | -197 | 2214.04 | 1982 | 1639 | -196 | 2213.01 | 0.047 |
| 3981  | 3162 | -397 | 4373.96 | 3977 | 3178 | -388 | 4379.22 | 0.12  |

7. Summarize
This article designed one type three direction metallization fiber-optic raster strain sensor through researched large quantity documents and existing fiber-optic raster sensor in the market, detail described the metallization fiber-optic raster sensor principle, design technology and structure design. Compare with the common fiber-optic raster sensor, this article designed metallization fiber-optic raster sensor has many advantages like smaller volume, big measure range, high measure precision, easy to install, firm structure and stable performance, etc. Through contrast the experiment test data and application in the actual engineering, the result shown that, this article designed metallization fiber-optic raster sensor completely meet the engineering measure requirements, able to be applied in the stress monitor of large-scale structure, like ships.

Acknowledgements
I would like to thank Ms. Yang Fang and Liu Huali the R&D Engineers of Wuxi Beetech Sensor Inc., and Mr. Xu Feng the general manager of Wuxi Beetech Sensor Inc., who put forward some literature of
fiber-optic raster sensor, and give me some constructive advice on the paper.

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