A plating method for metal coating of fiber Bragg grating

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We present a method for metal coating optical fiber and in-fiber Bragg grating. The technology process which is based on electroless plating and electroplating method is described in detail. The fiber is firstly coated with a thin copper or nickel plate with electroless plating method. Then, a thicker nickel plate is coated on the surface of the conductive layer. Under the optimum conditions, the surfaces of chemical plating and electroplating coatings are all smooth and compact. There is no visible defect found in the cross-section. Using this two-step metallization method, the in-fiber Bragg grating can be well protected and its thermal sensitivity can be enhanced. After the metallization process, the fiber sensor is successfully embedded in the 42CrMo steel by brazing method. Thus a smart metal structure is achieved. The embedding results show that the plating method for metallization protection of in-fiber Bragg grating is effective.

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Fiber Bragg grating (FBG) has the potential to be widely used as sensors in environmental applications, electronic noses, chemical industries, construction industry, air plane, and so on, because it has the advantages over conventional sensing techniques, including immunity to electromagnetic interference, remote sensing, ease in handling, low cost, small size, and light weight[1−5]. Embedding this sensor in an important part is a good method for monitoring temperature and strain changes. Embedding this sensor in composite material part has been widely developed[4,5]. But embedding it in a metal part is still a challenging work. The reason is that the optical fiber (mainly composed of SiO_2) is so fragile that it may be destroyed by the non-uniform stress, strain, or thermal loads in the embedding process. Moreover, the surface of the fiber is very smooth and cannot be easily wetted by any alloy. In particular, these difficulties can be overcome by adding a protective metal coat. In the previous work, sputtering, dip-coating, and plating methods were utilized to form the metal coating of optical fibers. Li *et al.* sputtered a thin titanium layer (about 1 μm thick) on the fiber to enhance the adhesion and then sputtered a nickel layer (about 1 μm thick) on the titanium layer[6]. In the work of Seo *et al.*, the fiber coating was applied by drawing the fiber through molten tin[7]. Sandlin *et al.* developed a plating method for metallization of the fiber, including chemical plating silver and electroplating nickel[8]. However, all these methods mentioned above have some disadvantages. For example, sputtering method is relatively expensive and low efficient. FBG may be destroyed by the molten tin in the drawing process and the service temperature of such a sensor is lower than 200 °C. Chemical plating silver is also expensive. Although silver is expensive, plating is a good method for metal coating optical fiber. In this letter, a plating method for metal coating of optical fiber and in-fiber Bragg grating is studied. Chemical and electro plating processes of copper and nickel are chosen. The method is practically applicable, due to its simplicity, cost-effectiveness, and lower processing temperature. In addition, the thickness of coating layer can be easily controlled by the plating method. The techniques for the chemical plating and electroplating are both well-documented. However, applications of these techniques for acquiring high-quality metal-coatings of desired thickness on optical fiber with in-fiber Bragg grating need further study. After metallization, the fiber sensor is successfully embedded in the 42CrMo steel by brazing method.

Optical fibers are normally coated with some organic materials, which must be removed before the metal coating process. The organic coating can be removed by immersing the optical fiber in acetone for $10-20$ min, which is followed by an ultrasonic cleaning process. Acrylate or any other polymer coating can also be removed by mechanical peeling with special scissors. The fiber surfaces, which are to be coated, must be cleaned by diluted nitric acid, acetone, alcohol, and de-ionized water for removing the metallic and oil impurities, and dusts.

The optical fiber can be coated with a thin nickel layer by reduction of nickel sulfate complex with sodium phosphite, propionic acid, and boric acid in a strong acid condition. And the optical fiber can be coated with a thin copper layer by reduction of copper sulfate complex with potassium sodium tartrate ($NaKC_4H_4O_6$), sodium hydroxide (NaOH), sodium carbonate, and formalin in a strong alkaline condition. In the chemical plating procedure, the optical fiber is firstly immersed in a solution containing tin chloride ($SnCl_2{\cdot}2H_2O$, 10 g/L) and hydrochloric acid (HCl, 40 mL/L) for about 10 min. Then it is immersed in an activation solution which contains palladium chloride ($PdCl_2$, 0.5 g/L) and hydrochloric acid (HCl, 5 mL/L) for $10-15$ min. Following the processes above, the optical fiber is immersed in a chemical plating solution. The optimum conditions of nickel and copper plating are presented in Tables 1 and 2, respectively. Figures 1 and 2 show the results of chemical plating under optimum conditions obtained with scanning electron

Table 1. Solutions and Optimum Conditions for Chemical Plating Nickel Conductive Layer

$NiSO_4{\cdot}7H_2O$	$20-30$ g/L
$NaH_2PO_2{\cdot}2H_2O$	$15-25$ g/L
$C_3H_6O_2$	$15-25$ ml/L
H_3BO_3	$15-25$ g/L
pH	$4-5$
Temperature	$80-85$ °C
Time	$2-3$ h

Table 2. Solutions and Optimum Conditions for Chemical Plating Copper Conductive Layer

$CuSO_4{\cdot}5H_2O$	$10-15$ g/L
$NaKC_4H_4O_6{\cdot}4H_2O$	$35-45$ g/L
NaOH	$8-10$ g/L
Na_2CO_3	$1-3$ g/L
$NiCl_2{\cdot}6H_2O$	$0.5-1$ g/L
HCHO (37%)	20 mL/L
pH	$12-13$
Temperature	$25-30$ °C
Time	$1-2$ h

microscopy (SEM). It is obvious that the thickness of the nickel or copper clad is uniform along the axial direction, and the clad layer is compact and flawless.

Temperature vibration experiment (30 °C and 400 °C vibration, by putting in and taking out the chemical plating fiber with a hot-oven) was carried out to examine the bonding force between the optical fiber and the metal coating. The result was examined by the optical microscope. After undergone three thermal vibration cycles, the surface of chemical plating coating was still smooth and no visible defect was found.

For the nickel electroplating process, a solution containing nickel sulfate ($NiSO_4{\cdot}7H_2O$, 180−260 g/L), nickle chloride ($NiCl_2{\cdot}6H_2O$, $30-50$ g/L), boric acid (H_3BO_3, $35-40$ g/L), and sodium lauryl sulphate ($C_{12}H_{25}SO_4Na$, $0.05-1$ g/L) was used. Before electroplating, surface electrical conductivity of the conductive coat (copper layer or nickel layer) should be checked with a clip-on ammeter (DM6056C, made in Shenzhen Shengli Corporation), then ultrasonic cleaned with diluted water. During the electroplating process, the conductive layer coated fiber was fixed to a home-made holder. The current feeding cable was then connected to one end of the fiber with conductive resin tape. The holder was set in the chemical solution just deep enough to prevent the conductive resin tape from touching the liquid. The parameters used for electroplating are presented in Table 3. Figures 3 and 4 show the perfect results of electroplating experiment with different conductive layer. It is obvious that no matter what kind of conductive layer was used, the surface

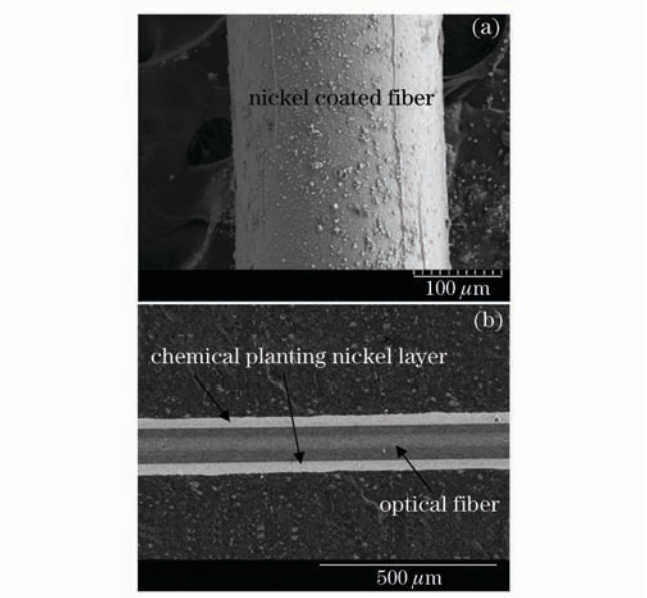

Fig. 1. SEM images of chemical plating nickel conductive layer under optimum conditions. (a) The optical fiber after chemical plating; (b) axial cross-section of the coated fiber.

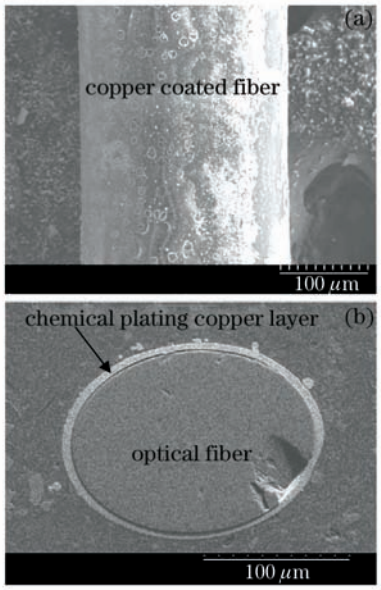

Fig. 2. SEM images of chemical plating copper conductive layer under optimum conditions. (a) The optical fiber after chemical plating; (b) radial cross-section of the coated fiber.

Table 3. Parameters for Nickle Electroplating

Positive Electrode	Pure Nickel Sheet
Current Detensity	$1.5-2.5$ A/m^2
pH	$3-5$
Temperature	Room Temperature ($20-30$ °C)
Time	$2-4$ h

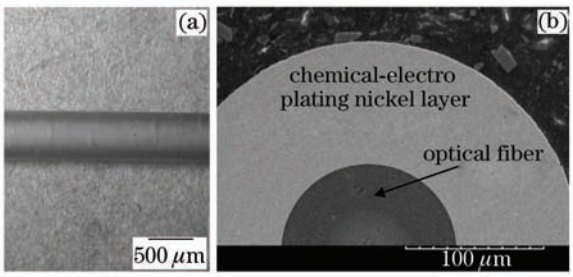

Fig. 3. Electroplating results with nickel conductive layer under optimum conditions. (a) The optical fiber after plating; (b) radial cross-section of the coated fiber.

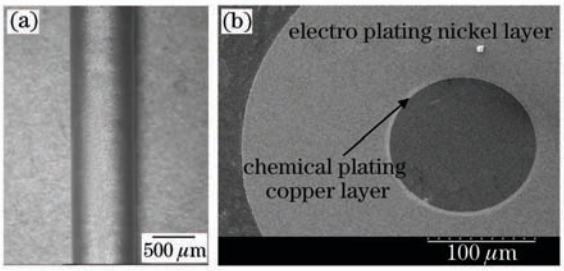

Fig. 4. Electroplating results with copper conductive layer under optimum conditions. (a) The optical fibre after plating; (b) radial cross-section of the coated fiber.

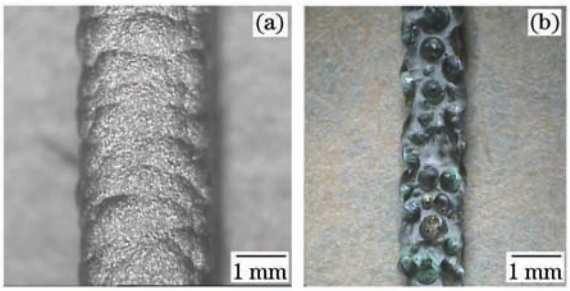

Fig. 5. Electroplating results under improper conditions. (a) Coarse characteristics; (b) porous characteristics.

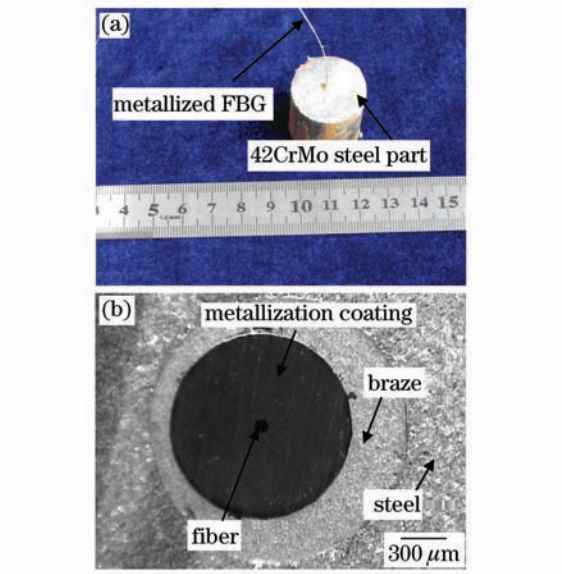

Fig. 6. (a) FBG embedded in a 42CrMo part; (b) radial cross-section of the part.

of the nickel clad was uniform, compact, and smooth. However, during the electroplating process, if the conductions are not proper, the surface of the nickel coat will be porous and coarse, as shown in Fig. 5. There is no visible borderline between the chemical plating nickel layer and electroplating nickel layer. However, an unclear borderline between the chemical plating copper layer and electroplating nickel layer exists because of the different chemical compositions.

The aim of the metallization for the fiber and in-fiber Bragg grating is to solve the problem of the fiber sensor protection and embedding in metal. Therefore, after metallization, a fiber sensor (before metallization, its central wavelength is 1531.657 nm) was brazed in a 42CrMo steel part using Sn-Ag-Zn filler metal, as can

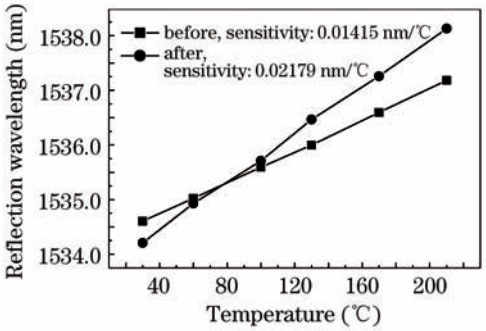

Fig. 7. Reflection wavelength versus temperature for the FBG sensor before and after metal coating and embedding.

be seen from Fig. 6. There was no obvious defect at the fiber/nickel layer interface. Thermal response experiment was carried out after embedding. Figure 7 shows the relationship between FBG reflection wavelength and temperature. Linear fitting results show that the temperature sensitivity of FBG was increased from 0.014 to 0.02179 nm/°C. These results show that the plating method for metallization protection of in-fiber Bragg grating is effective.

In conclusion, we present a method for metal coating optical fiber and in-fiber Bragg grating, including a chemical plating process and an electroplating process. Results show that, no matter copper, nickel, or any other metal layer employed as the conductive layer, the electroplating process can be successfully proceeded. Using this method, the optical fiber and the in-fiber Bragg grating can be well protected, and the surface of the coating is smooth and compact. The metallized FBG was successfully embedded in a 42CrMo steel part, and the sensitivity of the FBG was increased to 0.02179 nm/°C after the metallization and embedding process. Therefore, the plating protection method is effective.

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