On the Design of a Clad-Etched Fiber Bragg Grating Sensor for Magnetic Field Sensing Applications

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1 FBG-Based Magnetic Field Sensor

The design concept of such magnetic field sensor lies in the integration of a clad-etched fiber Bragg grating (FBG), which is sensitive to surrounding refractive index (SRI), with a magnetic-fluid coating as sensing element.

1.1 Magnetic Fluid

Magnetic fluid is a stable colloidal solution of ferromagnetic nanoparticles. The behavior of magnetic fluid depends on the external magnetic field and its refractive index shown to be magnetic field dependent [1–3]. The refractive index of a generic material n_{mat} is given by

$$n_{mat} = \sqrt{\varepsilon_r} = \sqrt{1 + \chi_m} \tag{1}$$

where ε_r is the dielectric constant and χ_m is the electric susceptibility of the material. The selected magnetic fluid consists of an aqueous solution of iron (II, III) oxide (Fe_3O_4—magnetite) magnetic nanoparticles (<50 nm) prepared by the chemical

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coprecipitation method [4]. Fe_3O_4 has a cubic inverse spinel structure which consists of a cubic close packed array of oxide ions where all of the Fe^{2+} ions occupy half of the octahedral sites and the Fe^{3+} are split evenly across the remaining octahedral sites and the tetrahedral sites. In this material, when the external magnetic field is perpendicular to the propagation direction of light, we have

$$\frac{\partial \chi}{\partial \mathrm{H}} < 0 \tag{2}$$

Then, the refractive index of the magnetic-fluid coating will decrease when the magnetic field increases.

1.2 FBG as Surrounding Refractive Index (SRI) Sensor

If the FBG is designed as a SRI sensor, the reflection spectra of the FBG will show a dependence on the refractive index of the media surrounding the fiber. A way to achieve sensitivity to changes in surrounding refractive index (SRI) is to excite evanescent waves in the media surrounding the fiber [5]. It has been proven that by etching the fiber in the grating region to reduce its diameter, SRI significantly affects the effective refractive index of the core, causing the Bragg wavelength to shift [6]. The Bragg wavelength is given by

$$\lambda_B = 2 n_{eff} \Lambda \tag{3}$$

where n_{eff} is the effective refractive index of the core and Λ is the grating period. Studying the dependence of the effective refractive index of the propagating mode, n_{eff}, on the design parameters of the FBG, in particular cladding diameter and SRI, is possible to find the relation between a shift in λ_B and the variation in the SRI that caused the shift. In the case of a magnetic-fluid coating, it is furthermore possible to establish a correspondence between the shift in the Bragg wavelength and the magnetic field the coating is subjected to.

$$\Delta\lambda_B = 2\left(\Lambda \frac{\partial n_{eff}}{\partial SRI} \right) \Delta_{SRI} \tag{4}$$

2 Device Modeling

In order to study the wavelength shift, a structure with a uniformly thinned cladding along the grating was assumed and a model of doubly clad fiber defined for the cross section [7, 8]. The dependence of the effective refractive index on both the cladding diameter and SRI was evaluated by numerically solving the dispersion equation of the double cladding fiber mathematical model. A two-dimensional mode analysis has been performed on a single-mode optical fiber defined by CAD with a fixed core radius of 4.1 μm and refractive index $n_{core} = 1.460$ RIU, cladding refractive index $n_{clad} = 1.455$ RIU and a variable cladding radius from 4.2 to 62.5 μm, and refractive index of the surrounding media SRI in the range of 1.33–1.45 RIU. The model was simulated in the COMSOL ambient, a commercial multiphysics FEM simulator, connected to MATLAB to sweep in cladding radius and SRI. The outputs of the electromagnetic analysis are the electric field distribution and the effective refractive index of the propagating mode, n_{eff}.

3 Results

The results show the effects of SRI and cladding radius on the electromagnetic properties of the device (Fig. 1). The Bragg wavelength of the thinned FBG shifts to higher wavelengths by increasing the SRI. The Bragg wavelength of the thinned FBG shifts sharply when the SRI is close to the cladding refractive index of the thinned FBG, near 1.460 RIU (Fig. 2). Moreover, the thinned FBG with the smaller radius has a higher sensitivity for the same SRI value (Fig. 3).

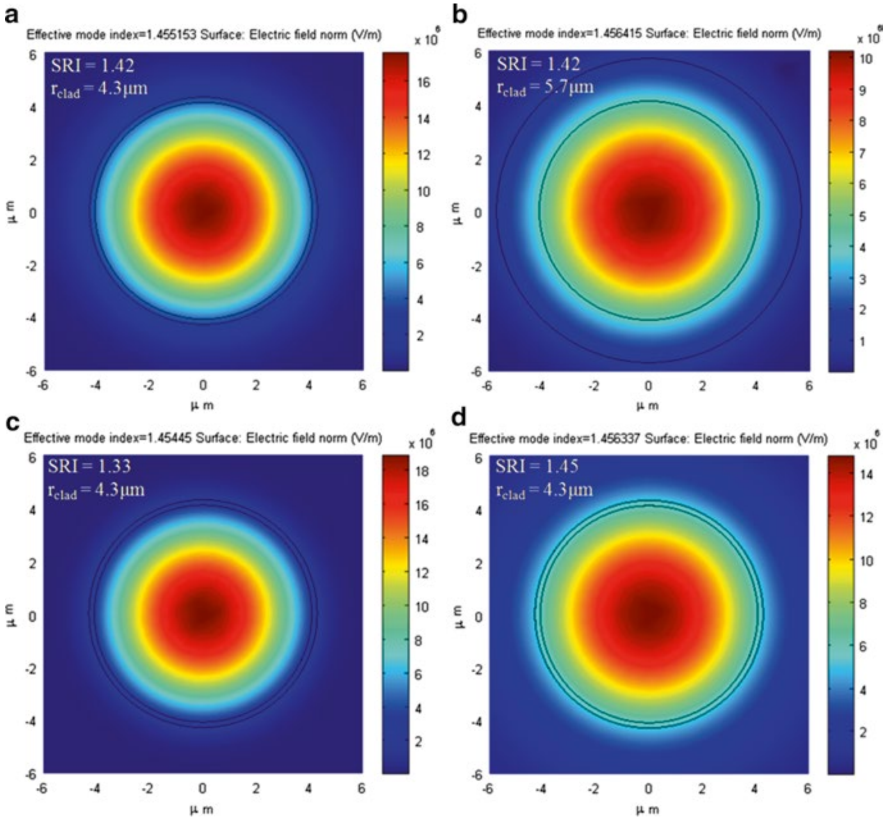

Fig. 1 Electric field distributions and mode n_{eff} for different values of SRI and cladding radius

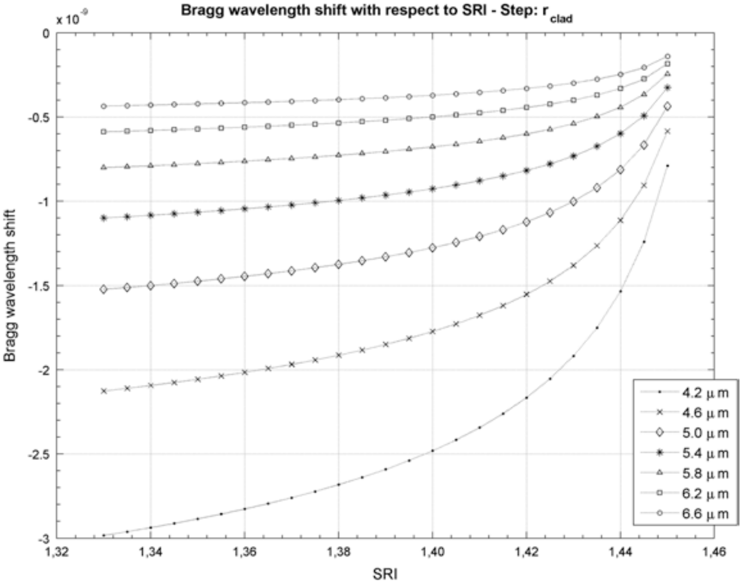

Fig. 2 Simulated Bragg wavelength shift as a function of SRI, for different values of r_{clad}

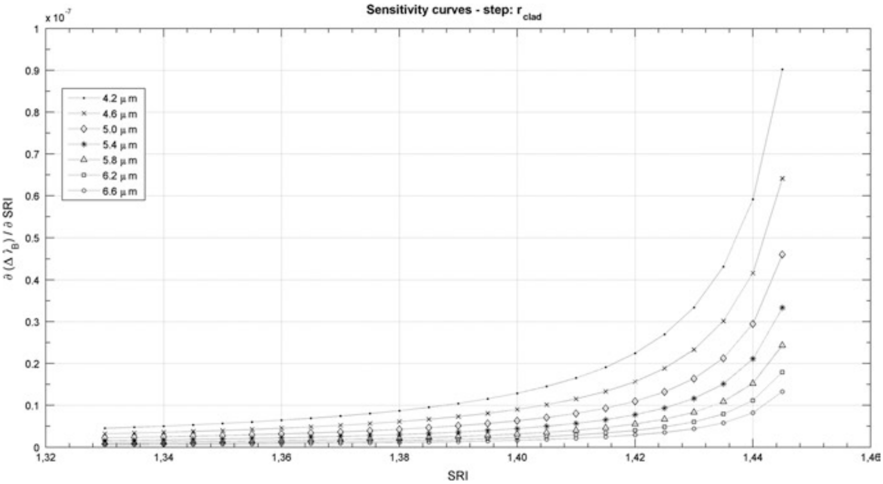

Fig. 3 Simulated sensitivity of a clad-etched fiber Bragg grating as a function of the SRI for different values of the cladding radius

4 Conclusions

The results obtained encourage our design concept and the development of a low-cost class of magnetic FBG sensors suitable for several kinds of applications, for low-intensity and high-intensity magnetic fields. The preliminary design and optimization phases carried out by means of the 2D FEM analysis permit to significantly reduce the cost and the development time of the sensor and to manufacture a customized device for each application.

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