D-fiber Bragg gratings for sensors

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Abstract

We introduce the surface relief fiber Bragg grating (SR-FBG) as an alternative to photo-induced fiber Bragg Gratings (FBGs). Instead of being written into the core of the fiber, as are standard FBGs, these SR-FBGs are placed in the cladding above the core. SR-FBGs have two important features that recommend them in as replacements for standard FBGs in certain sensing applications. The fact that the gratings are mechanical in nature allows them to operate at temperatures exceeding 1000 ^{0}C. Also, because the core of the D-fiber is elliptical it allows for multidimensional sensing.

Keywords: D-fiber, Fiber sensors, Fiber gratings.

1. Introduction

Bragg grating sensor technology is a well-established technique for monitoring temperature, strain and other environmental conditions in a variety of civil and military applications playing an increasingly important role in many applications. The most widely deployed type of fiber sensor is the fiber Bragg grating (FBG) sensor [1]. FBGs reflect light in a narrow wavelength band about the Bragg wavelength, and transmit light of other wavelengths. The reflection band shifts with changes in temperature, strain, etc. Shifts in the reflection peak are then correlated with the environmental variable to be measured to create a sensor.

Standard FBGs are fabricated by exposing optical fibers to an intense ultraviolet interference pattern. This exposure induces a periodic refractive index modulation in the fiber by modifying the structure of the core material [2]. This paper presents an alternative method for fabricating Bragg gratings in fibers by etching the gratings into the surface of a D-shaped optical fiber.

Figure 1 illustrates the cross-section of a D-fiber manufactured and supplied to us by KVH Industries, Inc. The two primary features of the D-fiber that set it apart from standard optical fiber are the elliptical core, and the proximity of the fiber core to the flat surface above the core.

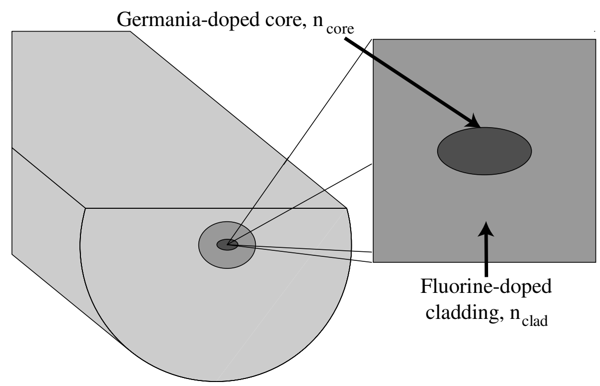

Fig. 1: Diagram showing the different regions of a D-shaped silica fiber.

This paper details the fabrication process and demonstrates the unique features of SR-FBG. It illustrates that the gratings can be formed using standard photolithographic equipment. It shows that sensors based on SR-FBGs can operate at and measure temperatures exceeding 1000 ^{0}C.

2. Grating fabrication

In this section we describe the process for creating a Bragg grating on the flat surface of a D-fiber. Figure 1 shows that a D-fiber has an elliptical germania-doped core surrounded by a fluorine-doped cladding and an undoped supercladding. The dimensions of the elliptical core are ~2 µm x 4 µm. The top of the core is ~13 µm from the flat surface of the fiber. This type of D-fiber supports a single mode at a wavelength of 1550 nm and allows two orthogonal polarizations of light to propagate.

To create gratings on D-fiber, we first remove the cladding above the core in a bath of buffered hydrofluoric acid (BHF) to give access to the light guided in the fiber. We then form a surface relief grating on the flat side of the fiber. A reactive ion etcher (RIE) directionally etches the photoresist and glass, transferring the grating into the fiber, which allows it to be used as a sensor. Figure 2 shows a diagram of a D-fiber in three successive stages of the fabrication process. It shows an unetched fiber, a fiber which has been etched to remove the cladding above the core, and a fiber having a surface relief grating on with photoresist and one showing the grating after removal of the photoresist.

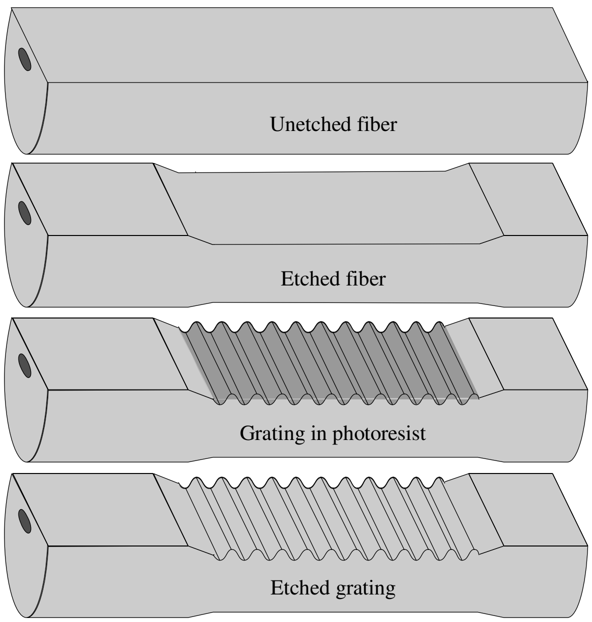

Fig. 2: Diagram showing a D-fiber in three fabrication stages. The top fiber is unetched, the middle one has been etched to remove the cladding above the core, and the bottom one has a surface relief grating etched into the fiber.

Simulations show that in order to create highly efficient gratings, they must be placed very close to the core. In order to control the etch depth we have developed [3,4] a technique that allows us to controllably monitor the etch and terminate it when a predetermined amount of cladding is left above the core.

2.1. Photoresist application, exposure, and development

With the fiber surface prepared we apply Shipley 1.2L photoresist over the length of the etched section of the fiber. The resist is thinned by mixing 2 parts photoresist to 1 part thinner. After applying photoresist, the wafer is spun in a commercial spinner for 1 minute at 6000 rpm. After spinning we soft bake the fiber for 1 minute at 90 °C.

Next we expose the photoresist with two interfering beams of light to create a surface relief grating in the photoresist on the flat side of the fiber. Figure 3 shows the Lloyd's Mirror arrangement that we use to expose the photoresist [5], in which the mirror and the fiber meet at a right angle. Half of the incident beam falls on the fiber which is mounted on a wafer. The other half falls on the mirror, which reflects it onto the fiber. The two halves of the beam combine to create an interference pattern on the surface of the fiber.

We design the gratings on the fibers so that the Bragg wavelength, λ_B, is 1550 nm. The resulting grating period, Λ, is given by

$$\Lambda = \frac{\lambda_B}{2N},$$

where N is the effective index of the mode in the fiber. The effective indices of both polarizations are very close to 1.45, so the grating period should be 534 nm in order to achieve a reflection peak at 1550 nm.

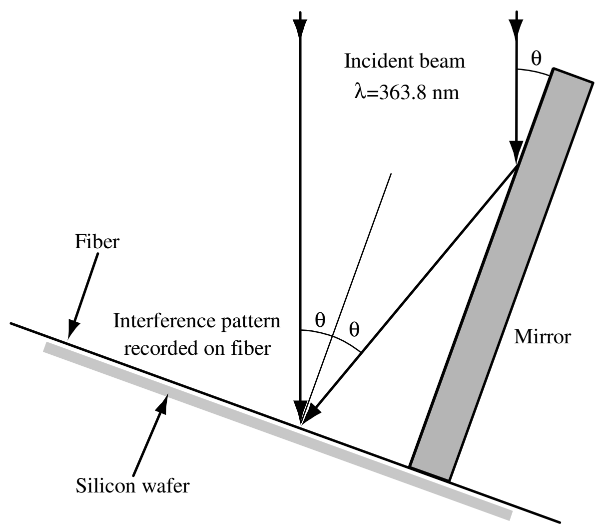

Fig. 3: Lloyd's mirror arrangement for creating an optical interference pattern on the fiber.

For the incident beam we use the 363.8 nm line of an argon ion laser. The recorded grating period is given by

$$\Lambda = \frac{\lambda}{2\sin\theta},$$

where θ is the angle between the normal to the fiber and the interfering beams. After exposure, we develop the resist on the fiber in Shipley 1.2L developer for 10 s then rinse it thoroughly with deionized water. At this point, there is a sinusoidal photoresist grating on the fiber with a peak-to-trough distance of ~300 nm.

2.2. Transfer of the grating into the fiber

To transfer the grating from the photoresist into the flat side of the fiber we place the fiber into the RIE. This step directionally etches both the resist and the glass, transferring the sinusoidal surface relief grating into the flat side of the fiber. To complete the process, any photoresist remaining on the fiber is removed with acetone and isopropyl alcohol.

2.3. Resulting grating pattern

Figure 4 shows a SEM image of a grating etched into the surface of a D-fiber using the procedure outlined above. While there are some irregularities in the grating, the structure of the grating is very clear. The gratings cover a large portion of the flat surface of the fiber, but there are intermittent areas where they are nearly washed out. The resulting grating is ~80 nm deep from peak to trough.

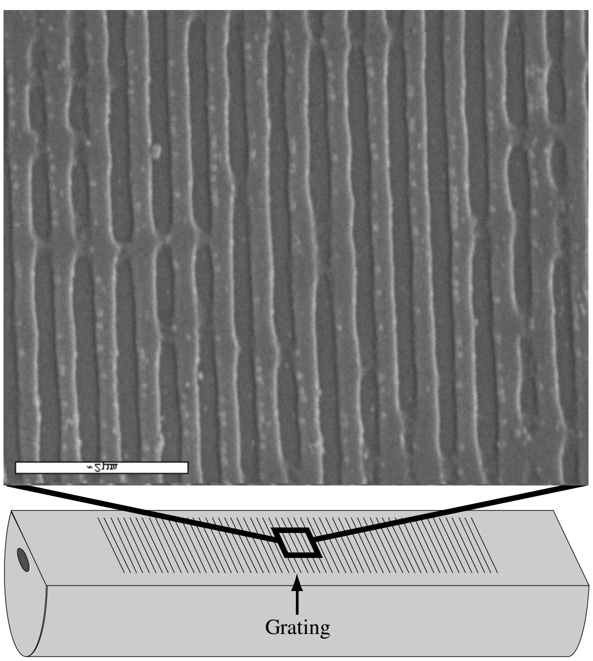

Fig. 4: SEM image of a grating etched into the flat side of a D-fiber.

3. Experimental Results

To test the performance of these gratings we launch a broad band amplified stimulated emission (ASE) source into the fibers and measure the transmission spectrum using an optical spectrum analyzer (OSA). At the Bragg wavelength, λ_B, there is a sharp dip in the transmission spectrum. This occurs because the grating back-reflects light in a narrow band about λ_B. The depth of the transmission notch varied from fiber to fiber, but the maximum notch depth we were able to see was 14 dB below the power value just to the left or right of the notch. Figure 5 shows the transmission spectrum of a SR-FBG. The notch is ~8 dB below the off-Bragg wavelength value and the notch linewidth is ~0.3 nm when measured 3 dB below the off-Bragg power.

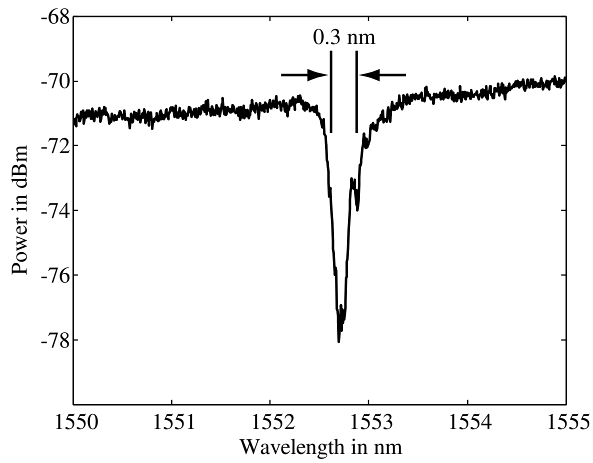

Fig. 5: Plot of the transmission spectrum of a SR-FBG.

The key to using FBGs as sensors is to correlate changes in the reflection/transmission spectrum with the environmental variable being measured. Different stimuli affect λ_B in different ways. For example, λ_B shifts with increases in temperature because of two different effects. First, thermal expansion causes the period of the Bragg grating to increase, and second, changes in the bulk indices of refraction of the fiber materials change the effective indices of modes in the fiber. Other factors, such as stress and strain also cause changes in the effective indices of modes, causing changes in λ_B [4].

Figure 6 shows the arrangement we use to test the high temperature sensing performance of the SR-FBG as a sensor. We launch the output of a broadband optical (ASE) source into the fiber and measure wavelength shifts in the transmission spectrum while the center section is heated from room temperature to more than 1000 °C. Figure 7 shows a plot of the shift of λ_B for a SR-FBG with temperature. All shifts are referenced to λ_B = 1552.6 nm, the Bragg wavelength at a temperature of 20 °C. The asterisks represent data points upon heating and the open circles represent cooling data. The line on the plot shows the linear fit to those data points. The slope of the line is about 15 pm/°C.

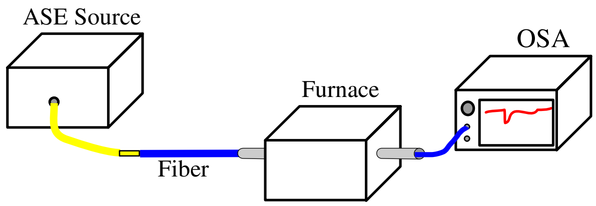

Fig. 6: Experimental arrangement to test high-temperature performance of SR-FBG.

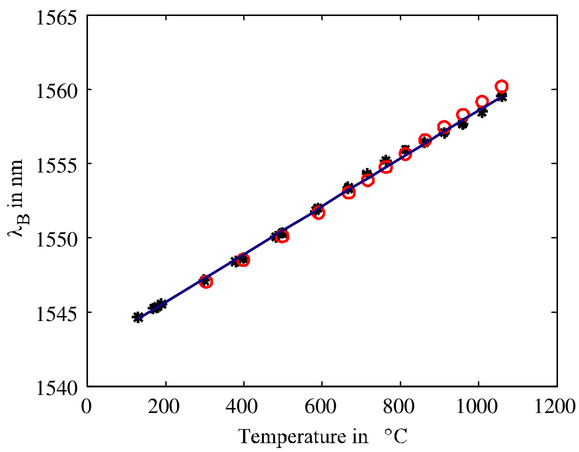

Fig. 7: Plot of the shift in Bragg wavelength vs. temperature for a SR-FBG. Insets show transmission spectra of the grating at different temperatures.

4. Conclusions

We have successfully fabricated surface relief fiber Bragg gratings on the flat surface of D-fibers just above the fiber core. SR-FBGs are a viable alternative to photoinduced FBGs for many sensing applications, including temperature, stress, and strain. We have analyzed these gratings and demonstrated their performance in a sensing application by measuring their temperature response. Since the corrugations of the grating are etched into the surface of the fiber, the grating does not deteriorate unless temperatures are near the melting point of glass.

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5. References

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