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Tunable Wavelength Filter Using a Bragg Grating Fiber Thinned by Plasma Etching

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***Abstract*—In this letter, we studied a tunable wavelength filter using a single-mode fiber Bragg grating with a cladding thinned by reactive plasma etching. Reflection wavelength shifts were demonstrated by controlling the effective refractive index or the period of the grating. When liquid paraffin was used for additional cladding on a thinned grating fiber of 19-μm diameter, the shift rate of 0.055 nm/°C was obtained. In the case of applying the tension to the grating region, the shift rate was 3.4 nm/100 V for the fiber of 41-μm diameter.**

***Index Terms*—Fiber Bragg grating, plasma etching, tunable-wavelength filter, wavelength-division multiplexing.**

I. INTRODUCTION

HIGH-DENSITY wavelength-division-multiplexed (WDM) multichannel optical communication systems are becoming increasingly important due to their ability to transmit a vast amount of information through optical fiber networks. Various optical functional devices must be realized in order to achieve flexible optical fiber networks. In particular, tunable-wavelength filters with a narrow bandwidth and a wide tuning range are useful devices for retrieving the desired information with a specific wavelength among the propagating WDM signals [1]. Fiber Bragg grating (FBG) devices have received significant attention as key devices in WDM technology, because the filter provides a narrow bandwidth, low crosstalk, and a flat-top passband compared to other filters.

Recently, in order to make the FBG tunable, some methods have been proposed [2], [3], in which the effective period of the grating is changed by applying tension, heat, or changing the index for the evanescent wave.

In those methods, the interaction between the external operation and lightwaves in the core is increased with decreasing clad diameter. Previously, the fabrication of optical fibers by wet chemical etching in a buffered HF solution has been reported [4]. However, it is unsuitable for the wet chemical etching to fabricate in a specified region of an optical fiber with high accuracy into various configurations, because the etching is isotropic. We have shown that reactive plasma etching enables the fabrication of optical fibers [5]. With this method, the optical fiber with various microstructures can be fabricated with precisely the same pattern as the mask patterning on it without making undercuts. In this study, single-mode Bragg grating fibers (10/125 μm core/clad diameter, 1550-nm grating wavelength, 10-mm grating region) with a cladding thinned by reactive plasma etching have been demonstrated to be useful for tunable-wavelength filters. The center wavelength of the Bragg reflector has been shifted by two methods; changing the effective refractive index by introducing additional cladding and applying tension to the grating region.

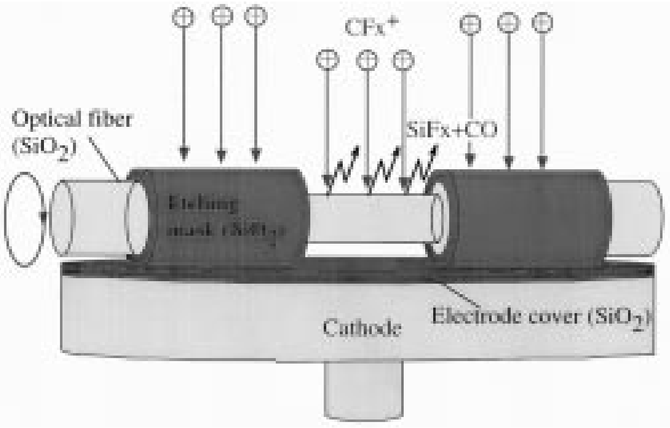

Fig. 1. Schematic of the experimental system used for reactive plasma etching of an optical fiber.

II. REACTIVE PLASMA ETCHING OF OPTICAL FIBER

Fig. 1 shows a schematic of the experimental system used for reactive plasma etching of an optical fiber. A CF_4 plasma was produced by two RF-powered (13.56-MHz frequency, 350-W maximum power) parallel-plate electrodes in a vacuum chamber pumped by a rotary vacuum pump. The cathode was water cooled and covered with a quartz plate in order to prevent the sputtering of nonvolatile compounds. CF_x ions were accelerated by an electric field in a plasma sheath and collided with the cathode perpendicularly. The etching of SiO_2 proceeds in the direction of motion of accelerated CF_x ions because silicon (Si) and fluorine (F), and oxygen (O), and carbon (C) react upon gasification into SiO_x and Co_x on the SiO_2 surface. If a rotating optical fiber is placed in the plasma sheath during the etching, thinning of the optical fiber becomes possible. The rotation of the optical fiber could be controlled from outside the chamber. Glass microcapillaries were adopted as an etching mask, which defined the irradiation region of the ion beam. In this work, each etching process was carried out

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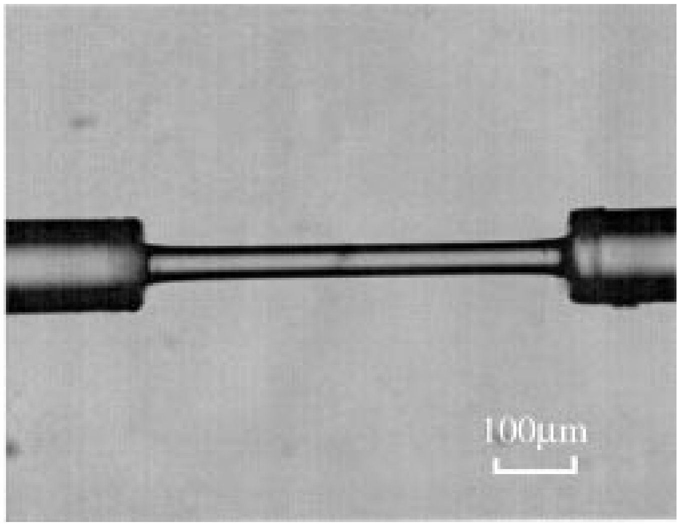

Fig. 2. Side view of an optical fiber thinned by plasma etching.

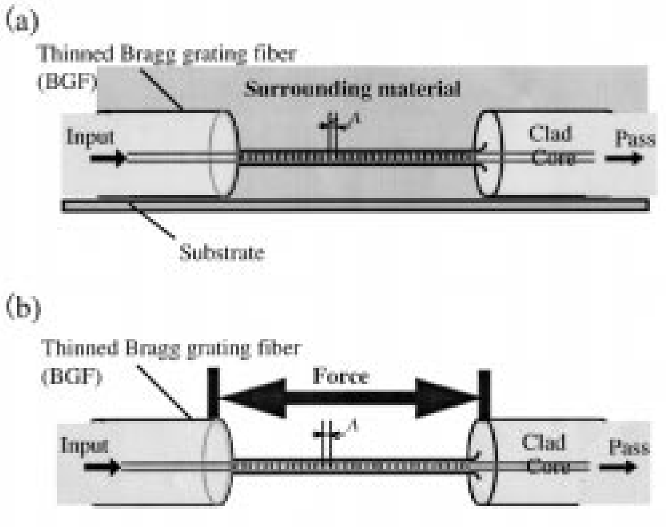

Fig. 3. Structure of the tunable wavelength filter with a thinned single-mode grating fiber. (a) Method 1: By changing refractive index of the surrounding material. (b) Method 2: By applying tension to the grating region.

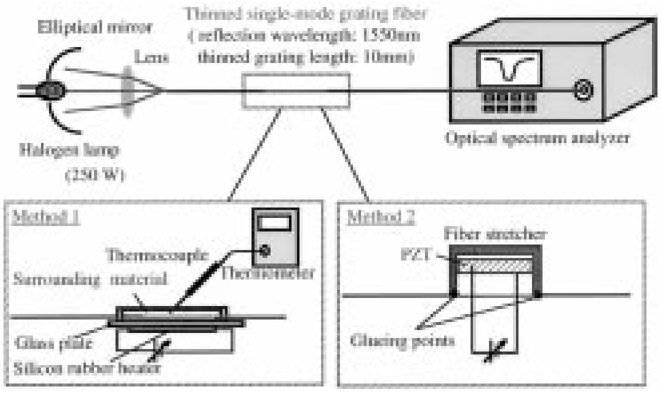

Fig. 4. Experimental apparatus for tunable-wavelength filter consisting of thinned single-mode grating fiber.

under the conditions of 13-Pa pressure, 150-W RF power, and 3-rpm rotational speed. Fig. 2 shows a side view of an optical fiber of which some cladding in a specified region was removed by reactive plasma etching for 10 h. The diameter of the etched region was reduced from 125 μm to approximately 45 μm.

III. STRUCTURE OF THE TUNABLE FILTER AND EXPERIMENTAL PROCEDURE

An FBG is a periodic refractive index perturbation, which is formed in the core of an optical fiber by exposure to an intense UV interference pattern. The periodic perturbation in the core index acts as a stopband filter. The grating selectively reflects light in a narrow bandwidth centered around

$$\lambda = 2n\Lambda \tag{1}$$

Here, λ is the reflection wavelength, n is the effective refractive index of the fiber, and Λ is the period of the grating. If the effective refractive index n or the period of the grating Λ is controlled, the desired reflection wavelength can be obtained. Fig. 3(a) schematically shows the first method in which the effective refractive index is changed by introducing additional cladding for the thinned fiber. In this method, the reflection wavelength can be controlled by changing the refractive index of the material surrounding the thinned grating region. This is equivalent to changing the effective refractive index n in (1). As the additional cladding layer, glycerine or liquid paraffin was used because they have refractive indexes close to that of the fiber cladding, and relatively large thermooptic coefficients $-2.2 \times 10^{-4}/^{\circ}\mathrm{C}$ and $-3.5 \times 10^{-4}/^{\circ}\mathrm{C}$ permitting efficient thermal tuning of the reflection wavelength.

On the other hand, the thinned grating fiber is also considered to be more advantageous in reflection wavelength shifts induced by applying tension to the grating region, because changes of the period of the grating are efficiently induced in the case of a fiber with a small diameter. Fig. 3(b) schematically shows the second method in which tension was applied to the grating region. This is equivalent to changing the period of the grating Λ in (1).

Fig. 4 shows the experimental setup for the tunable-wavelength filter consisting of the thinned single-mode grating fiber. Light from the halogen lamp (250 W) was focused on the input side of the thinned grating fiber. In the first method, the thinned grating region was surrounded by glycerine or liquid paraffin, the temperature of which was controlled by a silicon rubber heater, a thermocouple, and a thermometer. The reflection wavelength shift was measured as a function of the temperature of the surrounding material. In the second method, the reflection wavelength was shifted by applying tension to the grating region. A rectangular fiber stretcher manufactured from high-carbon tool steel was glued on both sides of the thinned grating region and driven by a piezoelectric actuator. The reflection wavelength was measured as a function of the voltage applied to the fiber stretcher. In all experiments, the center wavelength of the reflection bands was determined from the transmitted light spectrum measured using an optical spectrum analyzer at the output of the fiber.

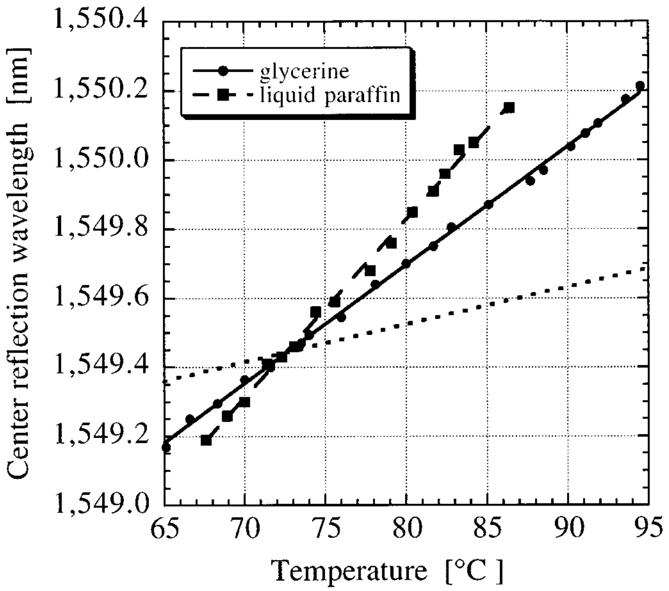

Fig. 5. Reflection wavelength as a function of surrounding material temperature.

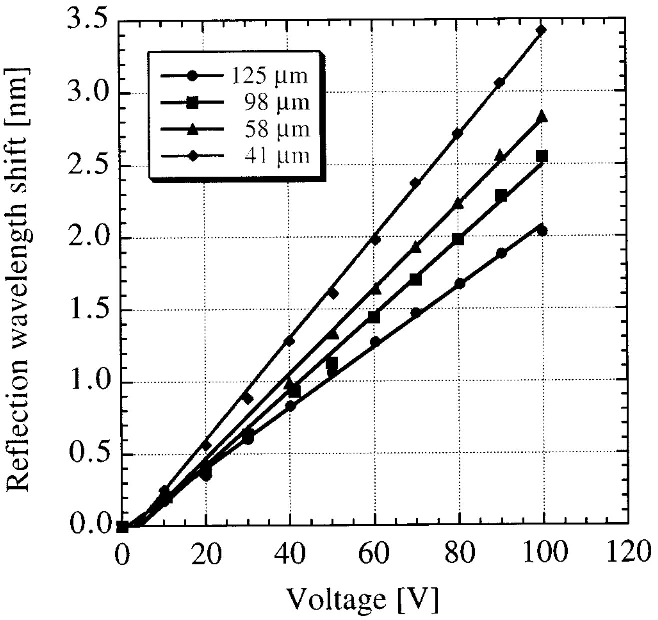

Fig. 6. Reflection wavelength shift as a function of voltage applied to fiber stretcher. (diameter 125 $f\hat{E}_m$, 98 $f\hat{E}_m$, 58 $f\hat{E}_m$, 41 $f\hat{E}_m$).

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 5 shows the shifts of reflection wavelength as a function of the temperature of different surrounding materials (glycerine and liquid paraffin). The length and diameter of the thinned grating region on the fiber were 10 mm and 19 μm, respectively. In Fig. 6, the solid and dotted lines represent the results for glycerine and liquid paraffin, respectively, and the dashed line represents the reference value of 0.01 nm/ °C for the shift rate of fiber glass at 1550 nm. The shift rate was 0.035 nm/ °C in glycerine and 0.055 nm/ °C in liquid paraffin. These values are, respectively, 3.5 and 5.5 times larger than the reference value. The differences between the shift rates of glycerine and liquid paraffin were caused by the shift rate of the refractive index of the material. The ratio of the shift rate in glycerine to that in liquid paraffin is 1.00:1.57. This ratio is almost the same as the ratio of the thermooptic coefficients of glycerine and liquid paraffin.

Fig. 6 shows the reflection wavelength shift as a function of voltage applied to the fiber stretcher in the second method. The diameters of the thinned grating region were 125 (without etching), 98, 58, and 41 μm. The shift rate was 3.4 nm/100 V when the thinned grating regions were 10 mm long and 41 μm in diameter. The value is approximately 1.7 times larger than that for the unetched fiber. Although thinning the grating region is effective to decrease the force applied to the fiber, the value of the wavelength shift is smaller than the theoretical values. This was caused by a mechanical loss at the adhesive part of the grating fiber and the stretcher.

The plasma etching, however, decreases the rejection rate, namely, the difference in the transmitted light intensity between the grating wavelength and other wavelengths was decreased to be 50%. It is considered that the decrease of the rejection rate was caused by the heat produced during etching. It is better to impress the grating after thinning the optical fiber to prevent the decrease of the rejection rate.

V. CONCLUSION

A single-mode FBG with a cladding thinned by reactive plasma etching at the grating region was used for a tunable wavelength filter. Reflection wavelength shifted by controlling the effective refractive index of the waveguide and/or expanding the grating mechanically. The shift rate of 0.055 nm/ °C was obtained when liquid paraffin was used for the additional cladding on a thinned grating fiber of 19 μm diameter. In the case of applying the tension to the grating region, the shift rate was 3.4 nm/100 V for the fiber of 41 μm diameter. The value was approximately 1.7 times larger than that for the fiber without etching.

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