Plasmon resonances in gold-coated tilted fiber Bragg gratings

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The transmission spectrum of fiber Bragg gratings with gratings planes tilted at a small angle (2°–10°) relative to the fiber axis shows a large number of narrowband cladding mode resonances within a 100 nm wide spectrum. When a gold coating with a thickness between 10 and 30 nm is deposited on the fiber, the transmission spectrum shows anomalous features for values of the outside medium refractive index between 1.4211 and 1.4499. These features are shown to correspond to the excitation of surface plasmon resonances at the external surface of the gold film. © 2007 Optical Society of America

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The possibility of using plasmon resonances[1] in metal-coated optical fibers has been the subject of many theoretical and experimental investigations.[2–6] For plasmon resonances to occur, the optical field within the fiber has to have nonzero amplitude at the fiber metal interface and a very specific value of axial propagation constant.[1] To allow an interaction between the guided core light and the metal film, most of the earlier work relied on metal-coated side-polished fibers, tapered fibers, or multimode fibers with relatively thin cladding layers.[2–4] More recently, two innovative approaches using gratings in single-mode fibers were proposed theoretically. The first considers using long-period gratings (LPGs) to couple light from the core mode to a forward-propagating cladding mode.[5] Using the phase-matching properties of LPGs, it was shown that it is possible to excite a particular cladding mode whose effective index is perturbed by a plasmon resonance of a metal coating on the fiber. The other proposed approach uses a short-period Bragg grating (FBG) in a specially designed single-mode fiber where the core is relatively large (26 μm) and the cladding is thin enough (2 μm) to have a nonzero core mode field amplitude at the outside cladding interface[6] (in this case again the grating is used to phase match the core mode effective index to the plasmon effective index).

There are many potential applications for such structures, especially in the optical sensing of chemicals as is commonly done using bulk-optic surface plasmon resonance (SPR) instruments.[1,7] Here we propose and demonstrate an alternative approach based on a tilted FBG written in standard telecommunications single-mode fiber. The weakly tilted grating is used to couple the core mode light to a multitude of cladding modes, depending on the light wavelength, as shown in Fig. 1.[8,9] By definition, the cladding modes have nonzero evanescent fields extending outside the cladding diameter and hence into the metal film. When the axial component of the propagation constant of the cladding mode equals that of an SPR wave, coupling to that SPR wave can occur. In contrast with the LPG and FBG approaches described previously,[5,6] a single grating design is sufficient to generate a wavelength-dependent set of cladding modes that are "interrogating" the metal film at various angles of incidence. This is most easily seen from the phenomenological representation shown in Fig. 2. Figure 2(a) shows the ray optic analogy of the coupling from a guided core mode to several cladding modes through a tilted short-period Bragg grating. Each of the modes can be individually "addressed" simply by changing the wavelength of the guided light, and each mode strikes the cladding boundary at a different angle of incidence. On the other hand, Fig. 2(b) shows the traditional attenuated total reflection method (usually referred to as the Kretschmann configuration) to excite and detect SPR waves by changing the angle of incidence of the light beam incident on the metal film.[1] The similarity is obvious, apart from the fact that the metal layer is deposited on a cylinder instead of a flat surface. When a cladding mode couples to an SPR, it will experience more loss than its neighbors. The effective index of the ith cladding mode (n^i_{clad}), is calculated from the resonance position $\lambda^i_{\mathrm{clad}}$ by[8,9]

$$\lambda^i_{\mathrm{clad}} = (n^i_{\mathrm{eff}} + n^i_{\mathrm{clad}})\Lambda/(\cos\theta), \tag{1}$$

where n^i_{eff} is the effective index of the core mode at $\lambda^i_{\mathrm{clad}}$ and Λ and θ are the period and the internal tilt

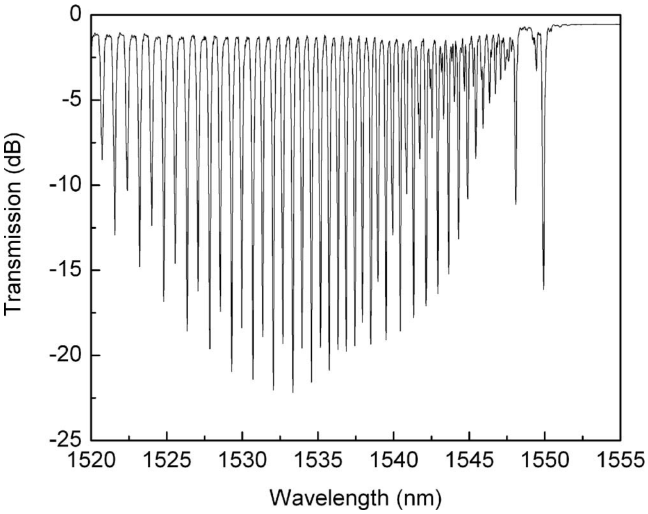

Fig. 1. Transmission spectrum of a weakly tilted FBG.

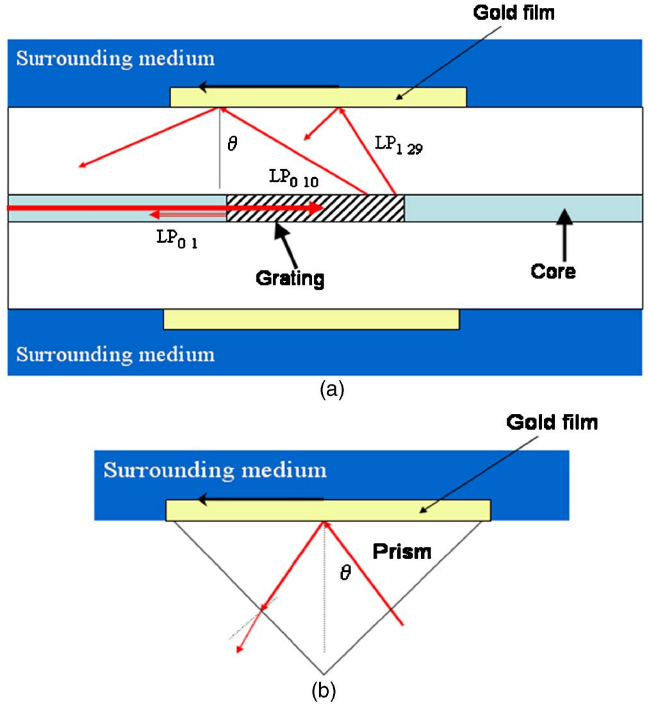

Fig. 2. (Color online) (a) Excitation of SPR waves with fiber modes through a weakly tilted FBG. (b) Kretschmann configuration for exciting SPR waves.

angle of the TFBG. Therefore, the resonance wavelengths of perturbed cladding modes will provide a direct measure of the effective index of the SPR waves through Eq. (1).

The fiber gratings were fabricated by using the standard process of KrF excimer laser irradiation of hydrogen-loaded Corning SMF28 fiber through a phase mask.[9] The required tilt was achieved by rotating the mask fiber assembly around an axis perpendicular to the fiber axis and to the plane of incidence of the laser light. The transmission spectrum of the grating used for the experiments reported is shown in Fig. 1. The longest wavelength resonance corresponds to the reflection of the core mode light onto itself (Bragg wavelength), while all the shorter-wavelength resonances correspond to the excitation of backward-propagating cladding modes. These modes are not reflected back to the source because they are rapidly attenuated by the fiber jacket as soon as they leave the grating region (where the jacket has been removed prior to fabricating the grating). For resonances between 1520 and 1560 nm, phase mask periods of the order of 1 μm are used. After fabrication, the gratings were heat stabilized by subjecting them to a rapid annealing at ~300°C, and the remaining hydrogen was removed by 12 h of heating at 120°C prior to gold deposition. In these preliminary experiments, we used a small-scale sputtering chamber (Polaron Instruments Model E5100) with the fiber positioned a few centimeters from the gold target. For flat samples in the same geometry, a gold thickness of 20 nm requires 1 min of deposition at a pressure of 0.1 Torr, a potential difference of 2.5 kV, and 18–20 mA of sputter current. To coat the fiber as uniformly as possible, two coating runs were made with the fiber holder rotated by 180° between the coatings. Under these conditions, the film uniformity around the fiber circumference is unlikely to be very good and may lead to some polarization dependence of the light transmission. The film thickness on the fiber that we quote in this paper is the value expected for the two sides of the fiber that directly face the sputtering target during the two coating runs. While thicknesses ranging from 10 to 50 nm were tested, we concentrate in the following on results obtained with a 20 nm thick nominal gold layer. We used a JDSU OMNI-2 Swept wavelength system to measure the transmission of our gratings: all the results shown were obtained by averaging the results for four orthogonal polarization states of the input light.

After the gold deposition, the fiber transmission spectrum is modified, but without measurable features of interest, indicating that the very thin gold layer has had an effect. When the gold-coated grating is immersed in liquids with various refractive indices

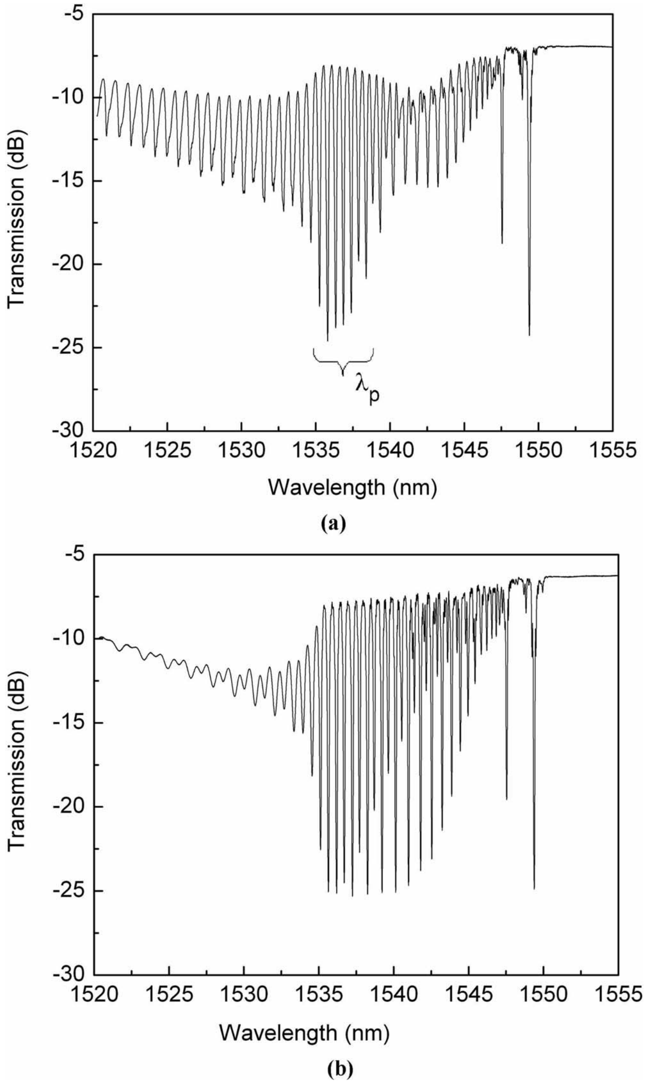

Fig. 3. (a). Transmission spectrum of the same grating as in Fig. 1 but with a 20 nm gold coating and immersed in a sucrose solution with $n_D = 1.4378$. The bracket indicates the peak position of the anomalous resonance. (b) Same as (a) but without the gold film.

(sugar solutions measured with an Abbe refractometer, giving the refractive index of the solutions at 589 nm, n_D with an accuracy of ±0.0002), anomalous resonances appear for certain very specific sugar concentrations [Fig. 3(a)]. These resonances are very different than those obtained for uncoated tilted fiber gratings,[8] as the comparative spectrum shows for the same grating in the same solution but without the gold film [Fig. 3(b)]. The peak position of the anomalous resonance [λ_P in Fig. 3(a)] is obtained by fitting the envelope of the cladding mode resonances. Figure 4 shows how λ_P changes as the refractive index of the outer medium is increased by small amounts. The spectral width of the envelope of the anomalous resonances is about 5 nm.

To validate our hypothesis that the anomalous resonances seen are indeed due to a plasmon effect, we now proceed to calculate some of the optical properties of these resonances. Using Eq. (1) to find the effective indices of the cladding modes within a resonance and the refractive index of silica near 1550 nm ($n=1.444$), we can calculate the angular spread of the equivalent angles of incidences (since the effective index is equal to the projection on the fiber axis of the refractive index in silica). For the data of Fig. 3(a), the angular spread is 3.5° (around a mean incidence angle $\theta=78°$). This angle of incidence agrees perfectly with the predicted value for gold-coated silica glass in sucrose solutions interrogated at wavelengths close to 1500 nm.[4] The angular spread of the resonance also corresponds well with typical values obtained for SPR measurements made with the Kretschmann configuration[7] (even taking into account that our deposition method likely results in nonuniform gold thickness around the fiber circumference, which would widen the resonances). Furthermore, the wavelength shift as a function of n_D is well approximated by a straight line with a slope of 454 pm/(10^{-3} change in n_D). Even considering the dispersion of our sugar solutions between 589 nm and the 1520–1560 nm region, this is again in excellent quantitative agreement with the expected behavior for contradirectional gratings in gold-coated silica fibers where shifts of the order of 100–500 pm/(10^{-3} change in n_ext) were theoretically predicted.[6] These observations support our hypothesis that the resonance seen is indeed due to a SPR that is perturbing some of the cladding modes. In particular, the effective indices of the plasmons that we observe are smaller than the glass refractive index but larger than the effective indices of the outer medium. This corresponds to the situation described theoretically in Ref. 5, where the plasmons are seen as perturbed cladding modes with a local electromagnetic field maximum at the outer metal boundary. Work is in progress to better characterize the gold layer and to evaluate the effect of its thickness on the optical properties, including the effect of polarization.

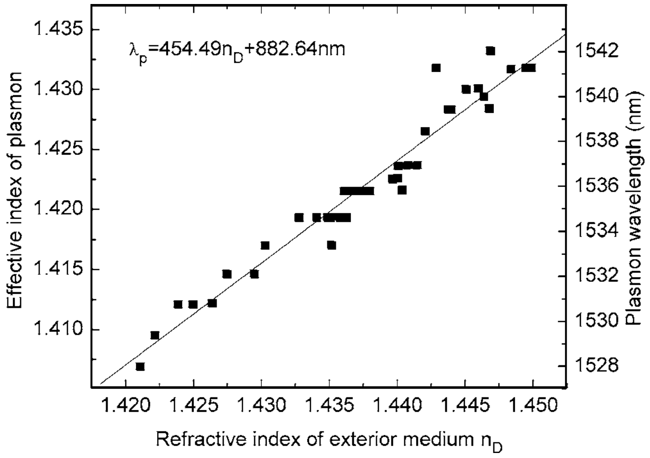

Fig. 4. Dependence of the plasmon resonance peak wavelength (λ_P) and corresponding cladding mode effective index on the refractive index of the external medium at 589 nm (n_D).

In conclusion, we have observed evidence of surface plasmon resonances in a gold layer deposited on a standard optical fiber in which a tilted fiber Bragg grating was written. The resonances are easily detectable and can be used for chemical monitoring through changes in the refractive index of the medium in which the fiber is located or through changes in the refractive index of the gold layer itself. Other metals with specific affinities for gaseous or liquid sensing could be used similarly. The device itself is very easy to fabricate with minimal adjustments of a standard FBG fabrication setup and uses standard, inexpensive, unmodified telecommunication-grade single-mode fibers. This configuration is applicable to other wavelength windows by changing the fiber type and grating period, especially visible wavelengths where SPR sensors are often used.

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