Multiple surface-plasmon resonance in uniform-waist tapered optical fibers with an asymmetric double-layer deposition

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Novel devices consisting of uniform-waist tapered optical fibers with asymmetric double-layer (metal plus dielectric) depositions have been recently proposed as refractive-index sensors. We study the properties of light transmission by use of this kind of devices, and we specifically perform a detailed study of the generation of surface-plasma waves in the structures. We show that multiple surface plasmons are excited for specific combinations of the constructive parameters of the devices and for specific ranges of the refractive index of the surrounding medium. The behavior also depends on the wavelength and the state of polarization of the incident light. The use of uniform-waist tapers allows for control of constructive parameters and an increase in the interaction length with the outer medium. We show how the plasmons are excited in the region of the taper waist by a coupling with the cladding modes guided in that area. This characterization shows the importance of the presence of a dielectric layer for selection of the operating range of the device. The results are useful for the design of new sensors. © 2005 Optical Society of America

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1. Introduction

Many sensors have been presented in recent years based on surface-plasmon resonance (SPR).[1] Surface-plasma waves are excited in thin metallic layers for given conditions of an incident field. Coupling of a field with a metallic structure can be achieved by use of different configurations. Once the advantages of using optical fibers for excitation of plasmon in comparison with the original Kretschmann configuration were made known, some possible options were proposed. Basically, the goal was to allow the field guided by the fiber to reach a metallic layer on which a plasmon was to be potentially excited. This was preferably done by evanescent coupling, for example, by polishing the cladding of the fiber and depositing layers on it (side-polished or D-type fiber devices).[2] Some sensors based on this principle have been proposed, many with application to environmental or chemical measurements. In these devices the modes guided by the fiber interact with the deposited multilayer structure, indicating that the spectral transmittance of the fiber is dependent on the parameters that characterize the deposition area, namely, the thickness and refractive index of the layers and also the refractive index of the outer medium. What is measured then is the power transmitted by the fiber, thus producing intensiometric or spectrometric, transmissive or reflective sensors. In this context, the excitation of a surface-plasma wave in a metallic layer is perceived as a drastic decrease of the fiber transmission, which is sensitive to any variation of the above-mentioned parameters and also shows spectral dependence. Energy of the guided mode is coupled to the surface-plasma wave, thus producing a well-defined dip in the transmittance curve, which is easily recognizable and difficult to explain by any

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cause different than plasmon resonance. The strong absorption associated with this coupling between the guided field and the surface plasmon is useful to explore the conditions of the superposed structure or the parameters of the external, surrounding medium. In many cases, different chemical or biological agents are used to enhance the responsivity and specificity of surface-plasmon-based devices. In general, it is convenient to provide ways to tune the behavior of the sensors by selecting specific configurations and choosing wavelength ranges well adapted to the desired measurands.

An alternative to side-polished fibers are tapered optical fibers. These elements are well known and their properties have been studied.[6,7] Essentially, taper is a narrowing in the diameter of a fiber produced in the intermediate region of it, in such a way that we can still have light transmission between the unaltered regions at each side of the taper. When the losses in the tapered region are low (which can be achieved with uniform-waist tapered fibers, as we depict below), we mean adiabatic tapered fibers.[8,9] In these devices, the light is guided by the cladding in the waist of the tapered region, since in that area the core has been reduced to a negligible diameter, which implies that the guided field can easily reach the outer medium so that any change in its refractive index produces a variation of the transmission of the fiber. To enhance that effect we can deposit a multilayer structure on the taper, in the same way that is done with D fibers. If one of these layers is metallic, we can excite surface plasmons on it when certain conditions are fulfilled. Some sensors have been proposed that use this principle.[10–14]

Recently, we introduced a new kind of device[15] that consists of uniform-waist tapered (UWT) single-mode fibers with an asymmetric double (metal plus dielectric) layer deposition and used them as refractive-index sensors. The parameters of these devices (taper length, taper waist diameter) can easily be controlled during the fabrication process. Although some work has been done in the past with UWT fibers with a single metallic layer, the addition of a second dielectric layer is an important feature, since it allows us to tune the response of the sensor to the desired range of measurands. Also, these devices are interesting from a theoretical point of view, since they exhibit a rich phenomenology in terms of SPR.

Here we study in detail the transmission properties of these devices, showing some significant facts such as evidence of multiple SPR in the structures, the dependence of those resonances on the type of deposition (in the whole extension of the taper or only in selected areas of it), the response of the devices to polarization (which is complicated because of the nonflatness of the deposited layers), and the dependence of their behavior on taper parameters. Since the devices are novel, this study is important to assess their possibilities as sensors and to define the initial conditions for the design of sensors based on their use for different measurands. Also, the richness and variety of the observed behavior is interesting in itself.

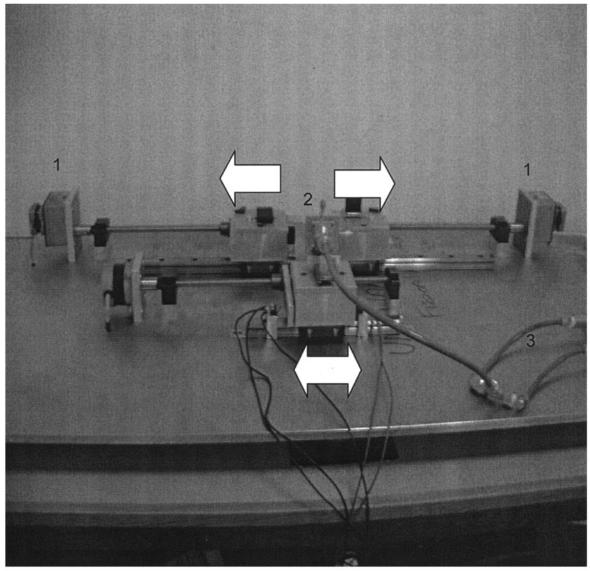

Fig. 1. View of the setup for production of UWT fibers (traveling-burner technique). Two motors (1) stretch the fiber while it is heated by a specially designed heater (2). The gas inlet appears at right (3).

2. Uniform-Waist Single-Mode Tapered Optical Fibers

Although uniform-waist tapered (UWT) single-mode optical fibers have been in existence for some time, they are still interesting to study. Villatoro *et al.*[16] depicted an experimental method to produce these kinds of device (essentially coincident with ours) and a simple theoretical method to characterize them. To obtain UWT single-mode optical fibers one must use a traveling-burner setup.[17,18] In this setup a heater is displaced in an oscillatory way to heat the complete length of the taper, while the fiber is gently stretched in opposite directions (Fig. 1). We then obtain a long waist with a uniform diameter, in contrast with the abrupt tapers that can be produced with a fiber splicer, which are called biconical tapers.[17] Biconical tapers have higher losses than uniform-waist tapers, which can be made almost completely adiabatic (meaning that all the power is transmitted across a taper with no loss).

UWT single-mode optical fibers are interesting devices from a sensing point of view. We can depict its behavior in terms of mode coupling among the different regions that comprise the tapered area. We can define five of these regions (see Fig. 2): I, unaltered fiber before the taper; II, transition region of decreasing diameter (usually exponential in shape); III, taper waist; IV, transition region of exponentially increasing diameter; V, unaltered fiber after the taper. If we consider a single-mode taper, we have an LP_{01} mode that travels along the fiber until region I ends. Then the power transmitted by the fiber will be coupled to cladding modes in region III through a transition in region II. If that transition is smooth enough we will have coupling between the LP_{01} core mode and the LP_{01} cladding mode of the waist region. We must take into account that in region III the core

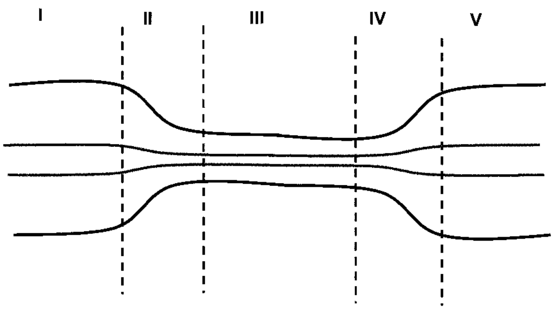

Fig. 2. Scheme of the profile of a tapered optical fiber. The regions are identified and are discussed in the text.

almost collapsed, since its diameter was reduced to a negligible value. In region III, in this way, we have a guiding dielectric cylinder that is multimode, so other higher-order modes can also be excited. If the fiber is kept straight, only axisymmetric LP_{0m} modes will appear, but modes of different azimuthal orders can receive energy if the taper is bent. This effect is used in some sensors. Some other sensors use the possibility of interacting with a guided field in the taper,[22,23] which is our case, and we will describe this kind of sensor in more detail later.

Whatever the interaction type we choose for the taper, the light after the tapered region has been affected by the variation of some measurand. This variation must be conveniently converted to an alteration of the spectral or total transmittance of the device, for example, by producing a SPR as will be seen later. In this way, the light that reaches region IV and is then recoupled into the unaltered fiber (region V) presents some losses that are attributed to the effect of the measurand. This is the basic scheme of all the tapered-fiber sensors. As can be seen, we have two important points:

(1) The fact that, in the tapered region, the field is guided by the cladding (this is true in the waist; in the transition regions we have a more complicated behavior because of the presence of a nonnegligible core and a varying thickness), and we can then easily access it.

(2) The possibility of adjusting the response of the system by depositing a structure of layers on the taper.

We also have the dependence of the taper on bending or strain, but these are effects that we do not use in the kinds of device we study and that we do not discuss here.

To this point, the discussion can be applied to both UWT single-mode optical fiber and to biconical tapers. However, these two different types of taper present some important differences. First, it is almost impossible to vary the parameters of the tapers in a controlled way when producing them with a splicer. The values of the length and the diameter of the waist are always limited. In particular, we always have short, nonadiabatic, abrupt tapers. We observed that the possibility of varying the taper parameters is important from the point of view of sensor design, but it is also important that we have a longer interaction length to enhance the response of the sensor. Having a longer waist also gives us the possibility of varying the length of the deposited layers: we will eventually know what the effect of this is. In general, once we have the setup to produce UWT fibers, the difficulty of fabricating them is comparable with that of making them with a splicer, and the possibility of varying their parameters is an added value of maximum importance.

Finally, we return to the important fact that we can tune the response of the sensors by acting on the tapered region, whether by inducing geometry changes or by changing its surrounding medium, replacing it with a more or less complex deposited structure. This is important because uncovered UWT fibers do not present interesting behavior except if the outer medium has a refractive index similar to the cladding one. Of all the possible coverings, those that are, in principle, capable of supporting SPR are the most important. To excite a surface-plasma wave we need a metallic layer, and some devices have been proposed that use this configuration. It is true that in some cases a second, thin layer is introduced to improve the adherence of the metal to the fiber, but the influence of this layer on the behavior of the device is negligible.[24] However, we have shown[15] that a second, thicker, dielectric layer, superposed upon the metallic layer strongly affects the response of the structure, displacing the resonance dip and widening the transmittance curve. This fact has already been demonstrated with D fibers[3,4] but, to our knowledge, no one has previously used a double-layer (DL) (metal–dielectric) deposition on a UWT fiber. By varying the thickness and refractive indices of these two layers we can, in principle, tune the behavior of the system in the desired way, for example, to obtain a higher response (i.e., a greater attenuation) for a given range of values of the outer refractive index. The versatility of these devices is then an important point to take into account, especially when they are so simple and so easily produced.

3. Double-Layer Deposition on Uniform-Waist Tapered Fibers

Figure 3 shows a DL UWT fiber with partial, asymmetric deposition. We used several taper waist diameters (between 31 and 40 μm) and lengths (approximately 30 mm). All the tapers were made in commercial single-mode fiber with a nominal transmission wavelength of 820 mm and they were quasi-adiabatic with original losses always less than 1 dB. We deposited an 8-nm-thick layer of aluminum and a 56-nm-thick layer of titanium dioxide. We used physical-vapor deposition. We chose the values because these were the layers we employed in a D-fiber-based sensor to measure salinity,[4] and it was interesting for us to compare the behavior of these new devices with that sensor.

The deposition was asymmetric mainly for two reasons. The first was the difficulty of achieving a uniform

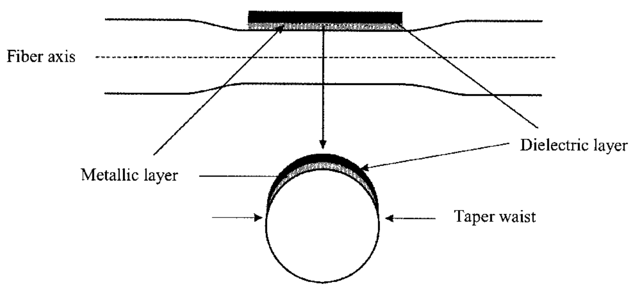

Fig. 3. Scheme of the DL UWT fiber devices. It must be taken into account that we used different kinds of deposition (as explained in the text) and for illustration purposes we show only one deposition, namely, that in which the deposition is made only on the waist region. Longitudinal and sectional views are shown.

complete (360°) deposition with two layers. In principle, the best way to achieve this is to use a rotating support to provide a uniform covering of the whole circumference of the taper, but this is not an easy experimental arrangement to use in a physical-vapor deposition chamber, especially when we need to deposit two different materials, the second one in an oxygen atmosphere. Another option is to combine three partial depositions, each covering approximately one third of the section of the taper, but the resulting thickness of the layers is not uniform. However, and this is the second reason for using them, the asymmetric devices should in principle present a more complex and interesting phenomenology than that of symmetric devices. In principle, we wanted to test their response to the polarization of the incident light, and the influence of the spatial distribution of the deposited layers in the tapered region. These asymmetric devices are also more easily comparable with the well-known SPR D-fiber-based sensors and having that reference is important to interpret the obtained results.

For the majority of the devices produced by us, the deposition was made on the whole length of the narrow part of the fiber (that is, the taper waist and the two transition regions). But we also produced, to study in a more detailed way the influence of the different spatial regions of the structure, tapers for which the deposition was made only on the waist or only on the transition regions. With respect to the sectional extension of the tapers, we believe that approximately one third of the circumference of the fiber was covered in a nonuniform way. We will confirm that this is also important, since the polarization dependence of the devices is not going to be completely equivalent to that of D fibers with planar layers. In our case it is not possible to define a unique direction of the TM polarization (which is the one that can excite surface plasmons), so the behavior of DL UWT fibers is less critical in that sense.

The excitation of surface-plasma waves on the metallic layer, after the parameters of the device have been fixed, depends on the refractive index of the outer medium and on the wavelength. If we consider the total output power transmitted by the device, thus integrating the spectral response, it will show dips for some values of the refractive index: these dips are associated with SPRs. In fact, the experimental curves shown below have a typical shape, which is well known in other devices based on surface plasmons. The transmittance curves of the structures outside the resonance range show no significant feature, and the well-defined absorbance peak can be explained by a coupling of the optical power transmitted by the fiber and the metallic layer. The other layers of the structure, as well as the external medium, play a significant role in the localization of the resonance peak(s).

According to the literature,[3] the typical range of refractive indices that can excite plasmons is above 1.4 when there is no dielectric layer. In our case, we can displace the dips to the 1.33 region which is convenient since our devices detect changes in the refractive index of aqueous solutions (which is of interest for environmental measurements and especially marine research). With respect to the wavelength range, we used 800 nm in the near-infrared region, and we also studied the dependence on wavelength for fixed refractive-index values.

4. Experimental Setup

The setup to characterize the devices is simple. As the source we used a LED with a peak wavelength of 830 nm and a spectral half-width of 50 nm. A LED is well suited to both intensiometric and spectrometric measurements. It is also an unpolarized source, so polarization of the light incident on the taper can be controlled, for example, by use of Lefèvre loops and an in-line polarizer. The taper with deposited layers is submersed in an aqueous medium whose refractive index is varied in a controlled way. In our case, we used a mixture of water with ethylene glycol, whose refractive index can be obtained from the value of the concentration of ethylene glycol by an empirical formula.[3] In this way we can vary the refractive index of the medium from 1.327 to 1.41, which is the range for which our selection of deposited layers is optimum, given the spectral range of the source. We can adjust the response of the sensor to any other desired ranges of refractive index or wavelengths by changing the parameters of the multilayer structure.

As a detector we used two different instruments. For the intensiometric measurements (where the total power transmitted by the fiber is determined) we used a commercial powermeter (HP 8152A). We normalized the results with respect to the value of the power transmitted by the system when the outer medium is air. For the spectrometric measurements we used a CCD spectrometer (Avantes AVS-SD2000) that allowed us to determine the spectral transmittance curves of the devices as a function of the outer refractive index. In this case we observed that the peaks of the curves were displaced when we changed the refractive index. This shift is the easiest parameter to use in potential applications of these devices as sensors.

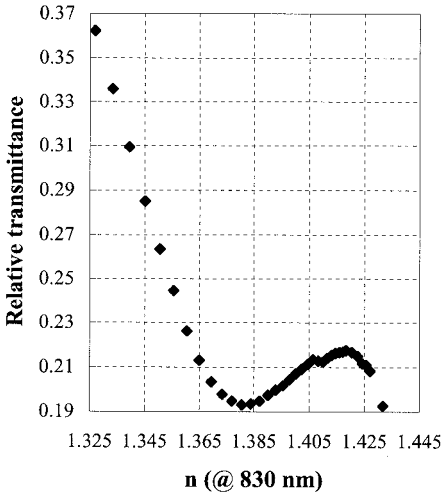

Fig. 4. Total output power transmitted by the devices (normalized by dividing by the transmittance with the air as the outer medium) as a function of refractive index of the outer medium for a taper with a waist diameter of 35 μm.

5. Experimental Results

A. Evidence of Multiple Surface-Plasmon Resonances

We measured the transmittance of DL UWT fiber-based devices with different waist diameters by varying the outer refractive index. Figure 4 shows a representative curve of the response of the system in terms of total output power (relative in the sense that it is compared with the value of the transmittance when the device is in contact with air) versus refractive index. As can be seen, a well-defined minimum appears, thus showing the excitation of a surface plasmon in the region of 1.37 refractive-index units. These results essentially coincide with those presented in Ref. 15, which we used to prove the feasibility of a refractometer based on DL UWT fibers. However, we performed a significantly more detailed study to determine the appearance of minima in the spectral transmittance curves. Although not all the minima must strictly correspond to plasmon resonances, the best-defined dips are undoubtedly associated with surface-plasma waves, and the measurements obtained permit us to draw maps of at least potential SPRs such as those shown in Fig. 5. In this case, we used a taper with a waist diameter of 40 μm and a waist length of 6.34 mm (28.30-mm total taper length), with a deposition covering the whole tapered area (transition regions plus waist). In Fig. 5(a) the spectral transmittance of the devices, as the outer refractive index varies, is represented as a three-dimensional (3-D) plot. Figure 5(b) represents this spectral transmittance by a contour plot with a gray-level scale. It can be seen how well defined the dips are, thus indicating the presence of surface plasmons. The locations of the minima are shown in Fig.

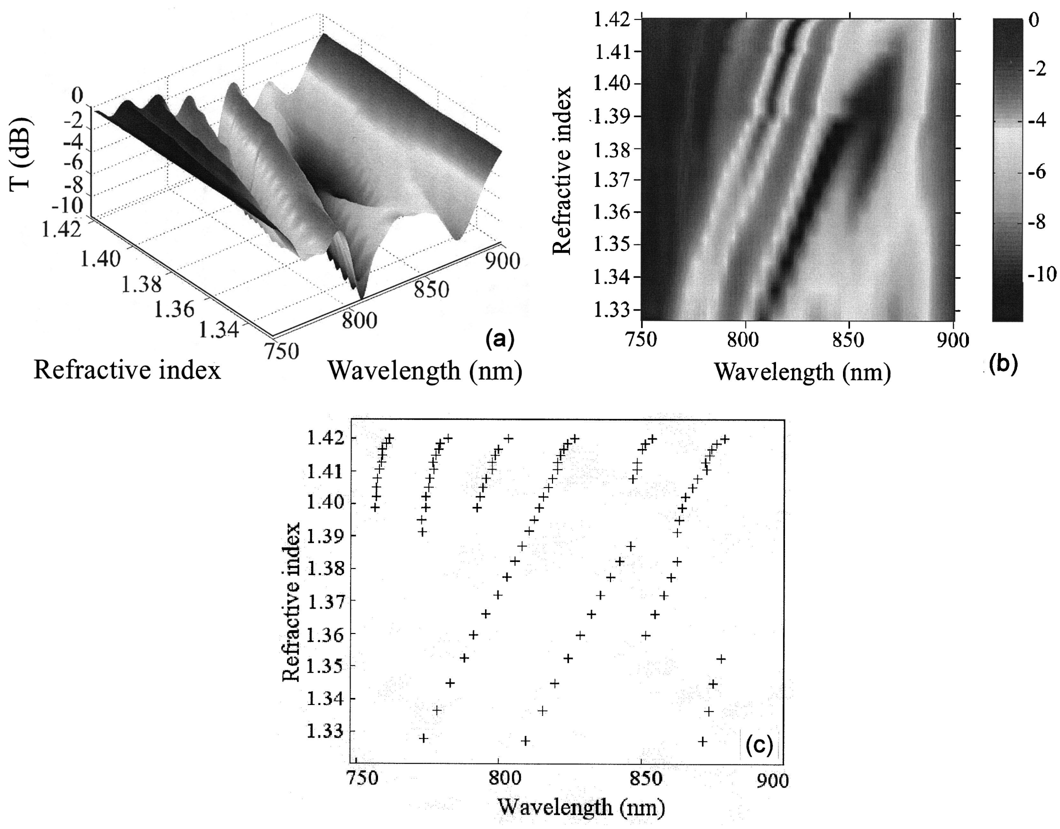

Fig. 5. SPR maps: (a) 3-D plot of the spectral transmittance of the device when the outer refractive index varies, (b) contour plot corresponding to the same case with transmittance shown in gray levels, (c) location of the transmittance minima.

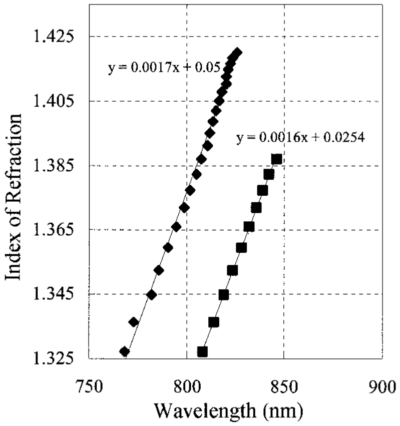

Fig. 6. Displacement of the first (diamonds) and second (squares) transmittance dips for the same device as in Fig. 5. Data were adjusted to regression lines.

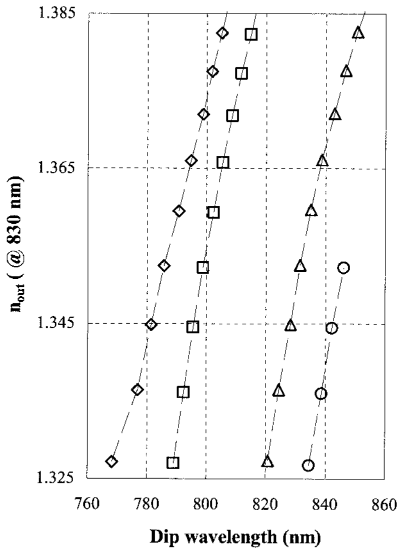

Fig. 7. Variation of the locations of the main transmittance dips with the waist diameter of the tapers (diamonds, 40 μm; squares, 37 μm; triangles, 35 μm; circles, 31 μm).

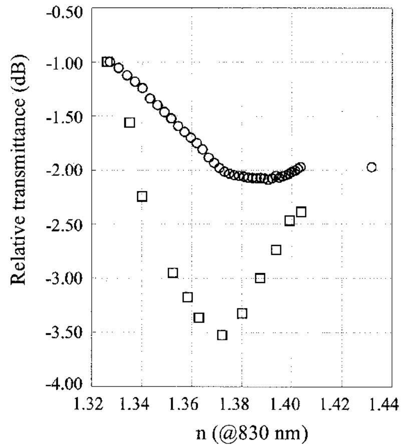

Fig. 8. Dependence of the behavior of the systems with polarization: circles, measurement taken without polarization control; diamonds, measurements taken with controlled polarization.

5(c), where we can see how the locations of the spectral dips are displaced as the refractive index varies. This is important since it means that the determination of spectral transmittance minima is a good way to measure refractive index with these devices, but the map gives us more information.

We can see how multiple SPR occurs. Having the possibility of playing with different dips for each measurement is good, because it can extend the dynamic range of the measuring method.[14] As we foresaw, the phenomenology of plasmon resonance in DL UWT fibers is richer than that of side-polished fibers. The key point here is that the thickness of the deposited layers is not constant. We could consider our layers to be a distribution of continuously varying thickness (both longitudinally and transversally with respect to the fiber axis), so the conditions of plasmon resonance vary in each part of the deposition and several plasmons can be excited even in the moderately narrow spectral range under consideration. A third important conclusion is that we find the plasmons in the same refractive-index region as when we worked with D-fiber devices, which can be due to only the presence of the dielectric layer, given that the structures reported in the literature until now, without dielectrics, do not cover that range.

Another remarkable fact is that the displacement of the plasmon locations is linear with the refractive index, which is shown more clearly in Fig. 6, where we also show a linear fit to the experimental point for the first two minima. It is obvious from Fig. 6 that DL UWT fibers are well suited for refractometric measurements and for any measurement in which the variation of the measurand is converted to refractive-index variations.

The location of the minima and their displacement obviously depend on the waist diameter of the tapers, as shown in Fig. 7 only for the first minimum. These minima are better defined for thinner diameters. We can see that plasmon resonance appears for longer wavelengths when the diameter increases for a given refractive-index value. This is interesting since we could select the operating spectral range by using different waist diameters. However, we must take into account that the dips for each waist diameter do not necessarily correspond to plasmon resonances of the same order.

B. Dependence on Polarization

As we said before, our layers are not plane, so it is impossible to define a TM polarization for all extensions of the deposition. This means that the dependence of the response of our device on polarization should not be too critical, although some dependence must still exist, since the deposition is still asymmetric. We confirmed this by the measurements shown in Fig. 8 (total output power measurements for a waist diameter of 37 μm and a total taper length of 29.3 mm), where we can see that the dip is better defined when the polarization of the incident beam is controlled, but the curve with no polarization control still shows some dependence on the outer refractive index and a less-defined minimum that could be associated with plasmon resonances.

C. Dependence on the Deposition Region

An important part of our characterization relates to the dependence of the behavior of the system on longitudinal extension of the deposition. Again, this is a study that we can consider specific to UWT fibers. In

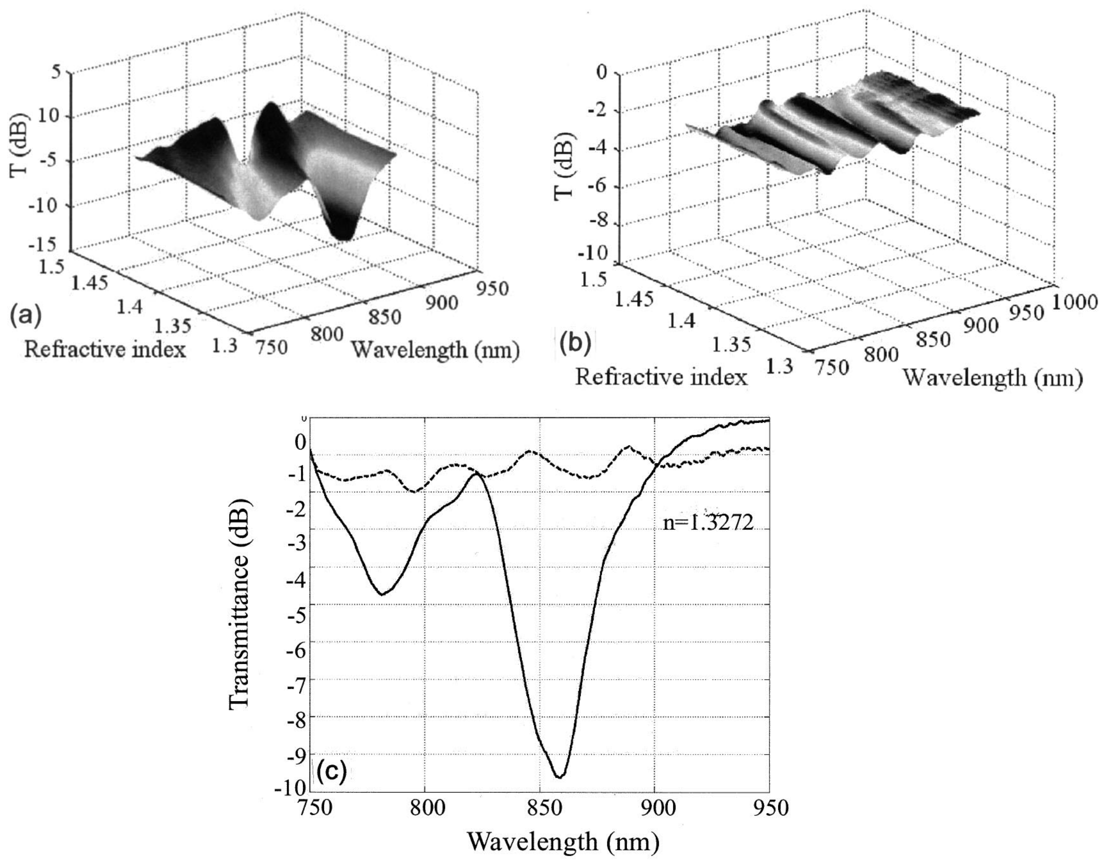

Fig. 9. Spectral transmittance of the devices as a function of longitudinal extension of the deposited region: (a) 3-D plot for a device in which the deposition is on the waist only; (b) 3-D plot for a device in which the deposition is on the transition region only; (c) comparison of the responses for both cases for a fixed value of the outer refractive index (upper dotted curve, transition region; lower continuous curve, waist).

biconical tapers it is difficult to deposit layers in different parts of the tapered region because the waist is too short. In side-polished fibers, there is, in principle, no difference depositing layers in different parts of the polished area, as long as we can keep the layers near the core of the fiber so the evanescent field can reach them. But in UWT fiber we can check if, as expected, the main part of the interaction takes place in the waist region, which could prove that the cladding-guided field in that area is responsible for plasmon excitation. The thickness of the guide, however, varies in a continuous way in the direction longitudinal to the axis of the guide. In principle, we can conceive that the conditions for plasmon excitation could be fulfilled also in the transition region, but, as we indicate, no well-defined dip appears in the spectral transmittance curves for the ranges of wavelengths and refractive indices that we consider. In that sense, we could even consider distributed sensing if we play with the displacement of the resonances as the taper thickness varies. In any case, the longitudinal extension of the deposition can be considered as an additional degree of freedom in the design and fabrication of sensors, a new one that contributes to the remarkable versatility of DL UWT fiber-based devices.

The effect of the extension of the deposition is shown in Fig. 9. Figure 9(a) shows a 3-D plot of the spectral transmittance of a device where the layers have been deposited only on the taper waist (region III in Fig. 2). Figure 9(b) shows a 3-D plot of the spectral transmittance of a device upon which we have deposited only on the transition regions (regions II and IV in Fig. 2). Finally, in Fig. 9(c) we compare the curves for an outer refractive-index value of 1.3272 for both cases. It is obvious that dips appear only in the first case and that much-less-defined minima appear when we deposit only on the transition regions. If we are interested in displacement of the dips, the contribution of the transition regions should be considered essentially as noise, and a more effective device could be produced if we deposit only on the waist. There the thickness of the layers does not significantly vary in the longitudinal direction (although we still have the sectional variation induced by the asymmetry of our depositions) and there is a better definition for the conditions of plasmon resonance.

6. Conclusions

We have studied in detail a novel type of guiding structure, double-deposited uniform-waist tapered optical fibers that are interesting from both a theoretical and a practical point of view. Based on our results we reached the following conclusions:

(1) Multiple plasmon resonance does occur in DL UWT fiber, i.e., coupling exists between the cladding-guided field and the deposited metallic layer for given combinations of parameters such as outer refractive index, wavelength, waist diameter, and thickness of the layers.

(2) Plasmons are excited in similar conditions as for double-deposited D fibers. This means that they can be based on similar theoretical principles and that DL UWT fibers are good alternatives to side-polished fibers; however, the two systems are not completely equivalent, and the differences can also be advantageously used in the design of sensors based on DL UWT fibers.

(3) The nonexistence of a privileged orientation in the layers implies a decrease in the dependence of the behavior of the systems on polarization, although this dependence does not disappear completely in asymmetric devices.

(4) The displacement of spectral transmittance dips with variation of the outer refractive index is a good parameter for refractometric measurements.

(5)SPR depends on the constructive parameters of the taper and especially on the waist diameter.

(6) SPR in DL UWT fibers occurs in the waist region; the dependence of this phenomenon on the longitudinal extension of the deposition has been studied here for the first time to our knowledge and reveals interesting aspects of the mechanism of plasmon excitation in complex waveguide structures such as DL UWT fibers that should be studied in more detail in the future.

Given the possibilities of DL UWT fibers as sensing devices, this study provides a basis for the design of new sensors and is also theoretically superior.

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