In-line fiber-optic sensors based on the excitation of surface plasma modes in metal-coated tapered fibers

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Abstract

Metal-coated tapered fibers are reported as refractive index sensors based on the resonant excitation of surface plasma modes supported by the metal coating. The devices are easy to fabricate and constitute an alternative to metal-coated side-polished fibers and to other sensors made up of bulk components. We report the fabrication and power transmission properties of quasi-circular devices and asymmetric devices. Both sets of devices can be operated as wavelength output sensors, as well as amplitude output sensors. The transmittance of quasi-circular devices is polarization independent and it changes more than 30 dB as a function of external refractive index.

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1. Introduction

Optical excitation of surface plasmon waves (SPW’s) has been used for more than one decade to develop a number of sensors. In 1982, the surface plasmon resonance technique was applied, for the first time, for gas sensing [1]. Since then, a large number of sensors based on this technique have been reported.

Surface plasmon waves are strongly dependent on the dielectric surrounding the surface and alterations in its refractive index lead to the modification of the properties of the SPW’s, resulting in a modification of the optical properties of the system. Surface plasmon excitation, in conjunction with immobilization techniques [2], gives a powerful tool for sensor applications. Several chemical [3,4], environmental [5] and biomedical [6] sensors based on this principle, have been reported. Most of the proposed configurations are made up of bulk optic components. In recent years, the surface plasmon resonance technique has been introduced into optical waveguides [7], giving rise to more integrated, compact and robust devices.

The use of optical fibers for surface plasmon resonance sensing was first introduced in 1993 [8]. The potential for sensor multiplexing and the possibility of developing remote sensing make the use of optical fibers attractive. In recent years, a configuration based on a thin metallic layer deposited onto a side-polished fiber (D-fiber) has been reported [9,10]. Since the SPW’s supported by the planar metal layer are TM-polarized, these devices exhibit polarization dependent responses and, in fact, they can be used as fiber polarizers [11,12].

Recently, optical fiber devices based on the excitation of SPW’s in metal-coated tapered fibers have been reported [13–16]. In a tapered fiber, the reduction of the core and cladding diameter causes the evanescent field to spread out into the cladding and eventually beyond the outer boundary. Thus, when a metal film is evaporated on a tapered fiber, the different surface plasma modes (SPM’s) supported by the metal film can be excited by the fiber mode. The tapering technique requires a simpler technology than the polishing technique and, in certain evanescent field applications, tapered fiber devices have been found more efficient than their side-polished fiber counterpart [17]. In our case, we will show devices with transmission dips deeper than 30 dB, while the side-polished counterparts, as well as the systems made up of bulk optics, typically exhibit transmission dips of around 10 dB. Moreover, tapered fibers maintain the circular symmetry of the original fiber, allowing the design of polarization insensitive devices.

In this work, we present some experimental results on the properties of metal-coated tapered fibers as sensors. Quasi-circular polarization insensitive devices and asymmetric polarization sensitive devices have been fabricated and their characteristics as refractive index sensors measured.
feasibility of such devices as wavelength-output and amplitude-output sensors is also discussed.

2. Fabrication of the devices

Using a travelling-burner technique [18], standard-telecommunications single-mode fiber was tapered adiabatically to a diameter $d_w$. The tapers had a uniform waist of several millimeters long (typically 20 mm) and they were low loss (<0.1 dB). Using standard metal-coating techniques a gold coating was thermally deposited onto the uniform taper waist. Gold was used because it has the appropriated refractive index in the wavelength of interest and it is resistant to oxidation.

Asymmetric devices were fabricated by a single gold deposition onto one side of the taper waist. A schematic cross-section is shown in Fig. 1a. The thickness of the gold layer varies from 0, at the edges, to a value $A$, at the top of the waist. The fabrication process of a quasi-circular device (Fig. 1b) included three identical gold depositions onto the tapered fiber waist, which was rotated 120° between two consecutive depositions. This produces a quasi-circular gold coating whose thickness is close to uniformity (13% thickness difference between maximum and minimum). Fig. 1c shows a longitudinal scheme of our devices.

3. Experimental results and discussion

The devices were tested using white light from a halogen lamp and an optical spectrum analyzer was used to record the transmission spectra. When polarized light was required, a bulk linear polarizer was inserted before the device. The fiber was placed in a straight line in order to preserve the polarization of the input light. The nomenclature used in this paper to describe the linear polarization of the light is shown in Fig. 1a. Commercially available Cargille liquids were used to specify the external refractive index. Although the metal-coated waist was several centimeters long, only a section $L$ of the central part was immersed into the fluids. All the spectra were normalized using the transmission spectrum when the device was in air.

3.1. Quasi-circular devices

Fig. 2 shows the transmission spectra of a quasi-circular device, for different external refractive indices. A single dip is observed and it migrates towards longer wavelengths as the external index increases. These measurements were carried out using non-polarized light. Measurements using linear polarized light demonstrated negligible polarization sensitivity.

The dip is caused by the resonant coupling between the fundamental mode guided by the taper waist ($HE_{11}$) and a hybrid SPM of azimuthal order $m = 1$ bounded to the metal layer. Hence, when the external refractive index changes, the dip shifts in accordance with the phase-matching condition between both modes [16].

Fig. 3 shows the center wavelength of the dip as a function of the external refractive index, for three devices with different gold coating thickness. A substantial shift of the dip is observed for small changes of the refractive index. As an example, the dip that corresponds to the 26 nm gold coating thickness device shifts from 900 to 1545 nm in the range 1.425–1.438 of refractive index. In all cases, non-linear behavior is obtained when a wide wavelength range is considered. Fig. 3 also shows the possibility of using the metal thickness as a tuning parameter for the sensor. This configuration where the measure of the wavelength response is used to determine the external refractive index would correspond to the operation of the devices as a wavelength-output sensor.

The same devices can be operated as amplitude-output sensors. In such a configuration, the power transmitted is
measured as a function of the external refractive index, for a fixed wavelength. Light of 1.3 µm was used in most of our experiments. Fig. 4 shows the normalized transmitted power as a function of the external refractive index, for two devices with 26 and 32 nm gold coating thickness. In both cases, a significant dip that shifts towards lower refractive index values as the metal thickness increases is observed. In a certain range, the attenuation decreases almost linearly as the refractive index increases. As indicated in Fig. 4, a linear variation of 27 dB in the range 1.434–1.438 of refractive index is obtained for the 26 nm metal thickness device. Such a sensitivity, in conjunction with an optoelectronic system able to measure variations of 1% in the optical power yields to a resolution higher than 1 \times 10^{-5} in the refractive index.

In all these cases, the response of the devices remain polarization independent which may simplify the optical arrangement in practical applications.

### 3.2. Asymmetric devices

The lack of circular symmetry of the asymmetric devices has, essentially, two consequences. On the one hand, the polarization degeneration of the SPM’s is lost and therefore, the transmission spectrum depends on the polarization of the input light. On the other hand, once the circular symmetry is lost, the incident mode, which is a hybrid mode of azimuthal order \( m \hat{\phi} \), can also excite SPM’s with azimuthal order \( m \neq 1 \) since they are not longer orthogonal. In fact, theoretical analysis demonstrates that surface plasma modes with \( m \neq 1 \) satisfy phase matching condition with the fiber mode in the wavelength range of interest [16]. Consequently, the spectra of these devices show more than one dip.

Fig. 6 shows the TM and TE transmission spectra of an asymmetric device, for three refractive indices. TM and TE spectra are clearly different and they show a series of dips, instead of a single dip, that move towards longer wavelengths as the external index is increased.

The increase of the metal coating thickness of asymmetric devices, like for quasi-circular devices, makes the series of dips to shift towards longer wavelengths, as Fig. 7 shows for three devices with different metal thickness.

The asymmetric devices can be operated as frequency output sensors as the quasi-circular devices of previous section. In this case, several resonances can be used to measure the refractive index. Fig. 8 shows the center wavelength of the first five dips of the TE spectrum as a function of the external refractive index. Substantial shifts of the dips are observed for small changes in the refractive index. Any refractive index value can be simultaneously monitored by several dips. This property can improve the accuracy of the measurements if it is combined with an algorithm that fits several dips to the calibration data. Analogously, a wide range of refractive index can be covered using the whole set of dips.
The asymmetric devices can also operate as amplitude-output sensors. Fig. 9 shows the normalized transmitted power of an asymmetric device as a function of the external refractive index, for TM and TE polarization. Only the ranges where the power transmission varies almost linearly with the refractive index are displayed. This figure includes the first and the second resonances and illustrates the feasibility of using each dip for different refractive index ranges. Again, substantial changes in the transmission are obtained for small changes in the refractive index. The use of these asymmetric devices as refractive index sensors requires a control on the polarization as it happens with the side-polished counterparts and the systems made up of bulk optics.

4. Conclusion

In this paper, we have reported the fabrication and basic characteristics of metal-coated tapered fibers and we have demonstrated the potential of these devices as refractive index sensors. The spectral response of the quasi-circular devices show a single dip that corresponds to the excitation of a hybrid plasmon mode of azimuthal order $m$. These devices are polarization insensitive, which can substantially simplify the sensor configuration in relation to other sensor schemes. The spectral response of the asymmetric devices is polarization sensitive and it shows a series of dips that corresponds to the excitation of different surface plasmon modes. The set of dips can be used to improve the accuracy of the measurements and the refractive index range of the sensor. High sensitivity and the feasibility of using both quasi-circular and asymmetric devices as wavelength-output or amplitude-output sensors have been demonstrated.

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References


Biographies

Antonio Díez received his PhD degree in physics in 1998 from the University of Valencia, Spain, where he was involved in the design and fabrication of optical fiber sensors. He joined the Optoelectronics Research Group at the University of Bath in May 1999 on a visiting fellowship funded by the Spanish government. He is currently working on acoustooptic effects in optical fibers.

Miguel V. Andrés was born in Valencia, Spain, in 1957. He received the Licenciado en Física degree in 1979 and the Doctor en Física (PhD) degree in 1985, both from the Universidad de Valencia, Valencia, Spain. From 1983, he has served successively as Assistant Professor and Lecturer in the Departamento de Física Aplicada of the Universidad de Valencia. From 1984 to 1987, he was visiting for several periods the Department of Physics, University of Surrey, UK, as a Research Fellow. Until 1984, he was engaged in research on microwave waveguides. His current research interests are optical fiber devices and systems for signal processing and sensor applications, and waveguide theory. Dr. M.V. Andrés is a member of IEEE, OSA and IOP.

José L. Cruz was born in Cuenca, Spain, in 1964. He studied physics at the University of Valencia and he received the PhD degree in physics in 1972. Initially, his career focused on microwave devices for radar applications, afterwards he developed photosensitive optical fibers in the Optoelectronics Research Group of the University of Southampton and currently he works as Profesor Titular in the Department of Applied Physics at the University of Valencia where he is conducting research on microwave photonics and fiber sensors.