Surface Modes in Antiresonant Reflecting Optical Waveguides with Rectangular Hollow Core

Federica Poli, Matteo Foroni, Simone Busanelli, Annamaria Cucinotta and Stefano Selleri
Information Engineering Department, University of Parma, e-mail: stefano.selleri@unipr.it

Abstract: *The guiding properties of antiresonant reflecting optical waveguides with rectangular hollow core have been deeply investigated. In particular, waveguides whose core is filled with water and ethylene glycol have been studied through a full-vector modal solver based on the finite element method, providing the dispersion and confinement loss curves in the wavelength range between 600 nm and 900 nm. Simulation results for both the considered waveguides have demonstrated the presence of anti-crossing points in the dispersion curves, which are associated with the transition from the guided mode to a surface one and, consequently, to high confinement loss values.*

Introduction

The idea of confining leaky modes in a low index core through cladding layers which alternate low and high refractive indices has been proposed for the first time in [1]. This principle is the basis of the so called Anti-Resonant Reflecting Optical Waveguides (ARROWs). Along with photonic crystal fibers [2], which exploit the photonic bandgap given by the periodic cladding material, ARROWs are the only structures which offer the possibility of light guiding in low index materials, such as air, liquid or gas [3, 4, 5, 6]. Moreover, these waveguides can be realized with the standard fabrication technology for integrated optical devices [3, 4, 6], thus providing advantages, such as compact size, planar geometry, potential for massively production, high level of chip integration. All these aspects fit well with the requirements for sensor design [7], from nano scale device [8] down to single molecule sensitivity [9] and can be exploited for many applications in different disciplines, including engineering, physics, biology and biochemistry.

So far, the analysis of hollow core ARROW has been limited only to few working wavelengths, fixed according to the particular gas or liquid filling the core [4, 5], and to the width of the cladding layers which assure the antiresonant effect. This approach allowed to successfully verify the light guiding in hollow cores, matching experimental results and theoretical expectations, but a general description of the waveguide behaviour in frequency and according to the material filling the core is still missing.

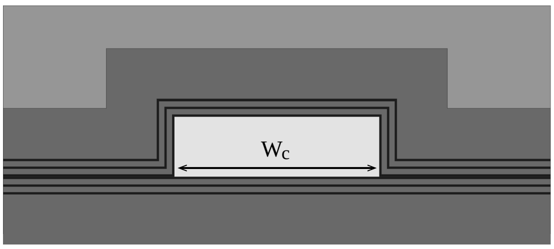

Fig. 1: Cross-section of the ARROW with rectangular hollow core. Three alternating layers of silicon nitride (black) and silicon oxide (dark grey) confine the light in the core region (light grey).

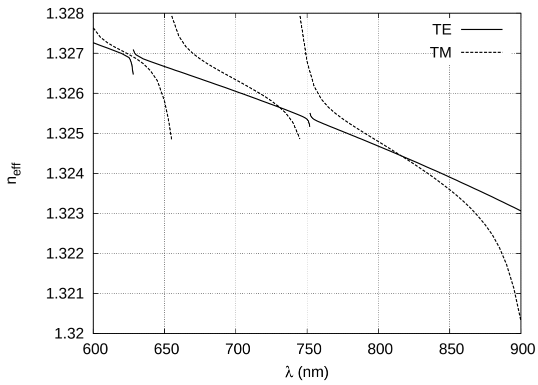

Fig. 2: Dispersion curves of the TE and TM polarizations of the fundamental mode for the ARROW with rectangular core of width $w_c = 12\ \mu m$, filled with water.

The present work provides an extensive spectral investigation of the ARROW properties with liquid-filled rectangular core. In particular, through a detailed analysis of the effective index, the confinement loss and the field distribution, the presence of surface modes have been demonstrated in these structures for the first time to the authors' knowledge. The appearance of these surface modes is quite similar to that of surface modes in hollow core photonic crystal fibers. In these fibers they are located in the thin silica layer surrounding the core [10] and are responsible of a strong reduction of the fiber transmission band [11]. In the same way, the surface modes considerably influence the ARROW performances, being responsible of the loss peaks which pollute the spectrum of the waveguides. Both TE and TM polarizations have been investigated in the wavelength range between 600 *nm* and 900 *nm*.

The present analysis has been performed by means of a full vector modal solver based on the Finite Element Method (FEM) [12], whose flexibility allows to describe any kind of cross-section and material, and guided as well as leaky modes. A complex formulation with the perfectly matched layers as boundary conditions [13] has been used. In particular, the FEM based

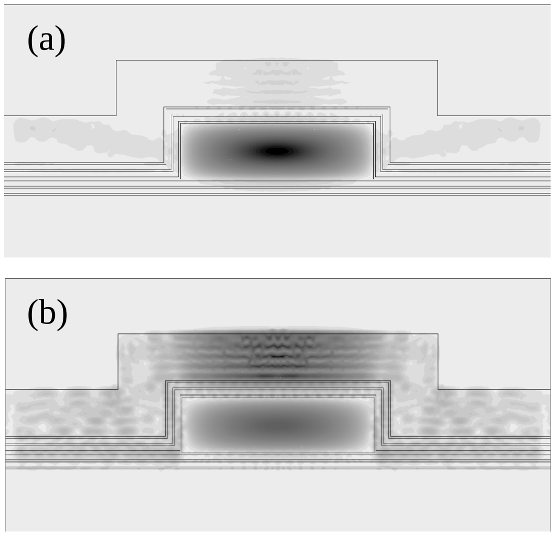

Fig. 3: Magnetic field modulus of the TE polarization of the fundamental mode at (a) $\lambda = 740$ *nm* and (b) $\lambda = 752$ *nm* for the ARROW with water-filled rectangular core of width $w_c = 12\ \mu m$.

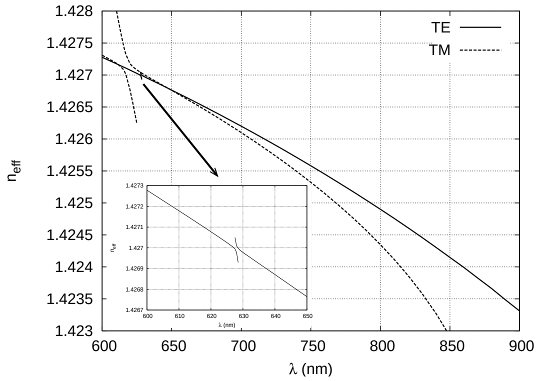

Fig. 4: Dispersion curves of the TE and TM polarizations of the fundamental mode for the ARROW with rectangular core of width $w_c = 12\ \mu m$, filled with ethylene glycol. Inset: particular of the anti-crossing point in the TE-polarized mode dispersion curve around 628 *nm*.

solver provides the field distribution and the complex propagation constant, that is the mode effective index n_{eff} and the attenuation constant α which yields the confinement loss due to the field leakage.

ARROW structure

The ARROW considered in the present work is the rectangular waveguide sketched in Fig. 1, optimized for a liquid-filled core. The guide has been previously designed and fabricated in [4]. The cladding is characterized by three periods of silicon nitride SiN and silicon oxide, or silica, SiO_2, whose refractive index is 2.1 and 1.46, respectively [4]. The thickness of the two layers, which is 126 *nm* for the SiN layer and 326 *nm* for the SiO_2 one, has been chosen in order to optimize the light guiding at 800 *nm* in a water-filled core with a refractive index of 1.33 [1, 4]. The height of the rectangular core is 3.5 μm, while its width w_c is equal to 12 μm [4]. The two layers at the top and at the bottom of the ARROW have been considered both made of SiO_2, while air covers the upper layers.

Core filled with water

The effective index n_{eff} of the TE and TM modes, computed for a water-filled rectangular core, are reported in Fig. 2. It is important to note that the dispersion curve for both the polarizations is broken in two points, called the anti-crossing points [10], which are around 627 *nm* and 752 *nm* for the TE fundamental mode, being significantly wider for the TM one. The presence of the surface modes is related to these discontinuities of the ARROW n_{eff} curves, as it happens for the hollow-core photonic crystal fibers, which support surface modes localized in the thin silica region surrounding the air-core [10, 11]. The magnetic field modulus of the TE fundamental mode is reported in Fig. 3 for two different wavelengths near the second anti-crossing point, that is 740 *nm* and 752 *nm*, clearly showing what happens to the ARROW fundamental mode. In fact, Fig. 3(a), at 740 *nm* the field is almost completely confined in the water-filled core, even if small components leak in the top and lateral regions of the waveguide. When the wavelength increases, the leaky components of the fundamental mode become stronger and stronger, and, at 752 *nm*, the TE-polarized fundamental mode is mainly confined in the layers surrounding the core, especially in the central region of the top silica layer, as shown in Fig. 3(b). The field maximum is no longer located in the hollow core. This guided mode change into a surface mode is described by a sharp decrease of the effective index curve. The field behaviour is specular as the wavelength decreases after the anti-crossing point on the other branch of the n_{eff} curve, passing from a surface configuration to a guided one. The same kind of transition can be observed also for the TM polarization.

Core filled with ethylene glycol

In order to analyze the influence of the liquid which fills the ARROW hollow core on the guiding properties, the same waveguide has been studied by considering the ethylene glycol as the core material. Ethylene glycol is characterized by a higher refractive index with respect to water, that is 1.43. This liquid has been often used instead of water for the experimental measurements reported in literature, since it evaporates more slowly than water, thus allowing for longer measurement times [4, 5, 6]. As reported in Fig. 4, the dispersion curves for the TE and TM polarizations present only one anti-crossing point in the short wavelength range.

With respect to the previous ARROW with a lower index core, the discontinuity is narrower for both polarizations, in particular for the TE one. As a conse-

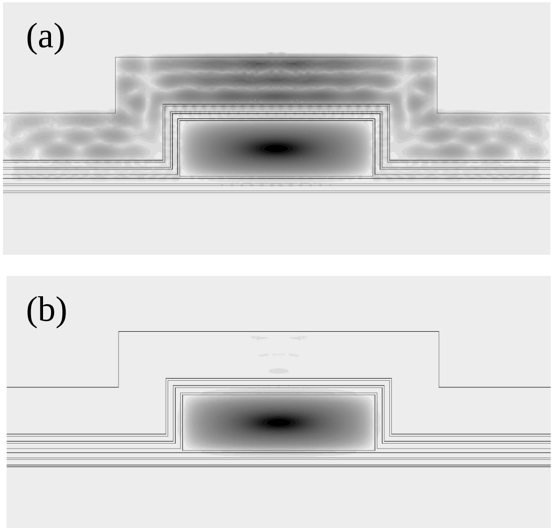

Fig. 5: Magnetic field modulus of the TE polarization of the fundamental mode at (a) $\lambda = 628$ *nm* and (b) $\lambda = 640$ *nm* for the ARROW with rectangular core of width $w_c = 12\,\mu m$, filled with ethylene glycol.

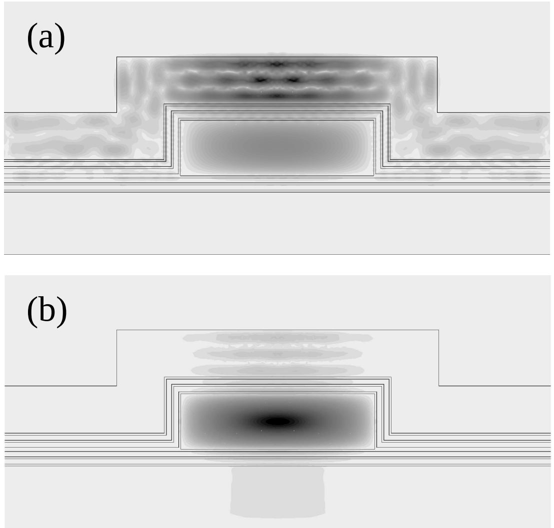

Fig. 6: Magnetic field modulus of the TM polarization of the fundamental mode at (a) $\lambda = 615$ *nm* and (b) $\lambda = 640$ *nm* for the ARROW with rectangular core of width $w_c = 12\,\mu m$, filled with ethylene glycol.

quence, the waveguide with the ethylene glycol-filled core can be used in a wider wavelength range, even around 750 *nm* where the water-filled core ARROW can sustain only a surface mode, instead of the one confined in the core for TE and TM polarizations.
Besides the wavelength shift and the narrower discontinuity, the qualitative behaviour is the same as the one described in the previous Section. In particular, Fig. 5 shows, for the TE polarization, the transition from surface to guided mode, when the wavelength increases from 628 *nm* to 640 *nm*, going away from the anti-crossing point.
In order to demonstrate the influence of the fundamental mode polarization on the surface mode behaviour, the distribution of the magnetic field modulus for the TM polarization is reported in Fig. 6 for two wavelength values similar to the previous ones. Being larger the discontinuity in the dispersion curve of the TM-polarized mode, and centered around a shorter wavelength, that is 620 *nm*, the field at 615 *nm* has been chosen in order to show the surface mode behaviour, while the wavelength has been kept fixed to 640 *nm* for the guided one. Notice that the field distribution for the surface mode with TM polarization, shown in Fig. 6(a), is similar to the one previously reported in Fig. 5(a) for the TE-polarized mode, so the change of the guided mode into the surface one occurs for both the fundamental mode polarizations. Moreover, it is interesting to compare the characteristics of the field of the guided mode for the two polarizations at the same wavelength of 640 *nm*, which is reported, respectively, in Fig. 5(b) and 6(b). While the TE-polarized field is completely confined in the ARROW liquid-filled core, some field components for the TM polarization leak into the higher refractive index layers at the top and the bottom of the rectangular core. This observation is also confirmed by the analysis of the confinement loss discussed in the next Section.

ARROW confinement loss

The Confinement Loss CL of the modes are deduced from the attenuation constant α as

$$CL = 20\alpha \cdot \log_{10} e \cdot \frac{1}{100} \simeq 0.087 \cdot \alpha \quad [dB/cm]\,, \quad (1)$$

and are reported in Fig. 7 in the wavelength range between 400 *nm* and 1000 *nm* for the TE-polarized fundamental mode, comparing the two hollow core ARROWs, filled with water and ethylene glycol. The wavelength range has been enlarged toward the lower wavelengths, in order to clearly observe the curve behaviour. Notice that the transmission spectrum of both the waveguides is abruptly interrupted by high CL peaks at the wavelengths corresponding to the anti-crossing points in the dispersion curves, due to the surface mode presence. Notice that two additional surface modes, one at about 466 *nm* for the ethylene glycol-filled core waveguide and one around 945 *nm* for the water-filled core one, have been demonstrated through this wider-band analysis of the confinement loss.
Looking at Fig. 7, it is important to underline that the liquid in the waveguide core strongly influences its confinement loss behaviour. In fact, both curves present a U-shaped profile with a minimum value, which is located around 780 *nm* when considering water and down shifts when filling the core with ethylene glycol. The CL levels provided by the two materials are, however, quite different. As can be expected, the refractive index of the ethylene glycol, higher than the water one, helps in focusing the field thus resulting in much lower losses. In particular, it is possible to

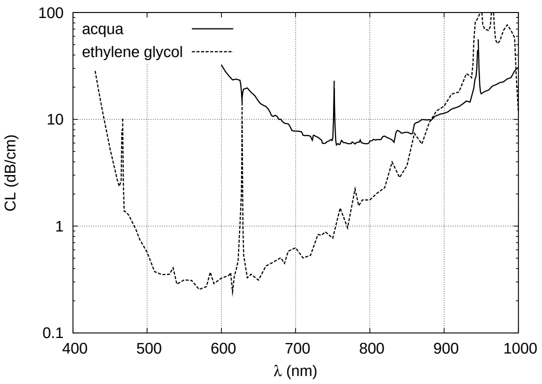

Fig. 7: Confinement loss versus the wavelength of the TE polarization of the fundamental mode for the ARROWs with rectangular core of width $w_c = 12\ \mu m$, filled with water and with ethylene glycol.

identify a spectral range of almost 300 *nm* where the guide presents CL lower than 1 dB/cm, even if broken off by the loss peak related to the anti-crossing point around 628 *nm*. The water core ARROW never reaches such CL values, being the minimum slightly lower than 6 dB/cm. This, however, does not prevent possible applications, for example in sensing systems, where typical waveguide lengths are of the order of few millimeters or few centimeters [4, 8]. The TM mode CL has been calculated as well for both the core liquids, showing, as expected, higher values with respect to the TE polarization. In particular, confinement loss higher than 3 dB/cm and 100 dB/cm has been obtained in all the considered wavelength range, respectively, for the ethylene glycol-filled and the water-filled ARROW. These high values render the TM polarization actually not guided in water-filled core ARROW, even for very short waveguides.

Conclusion

A detailed analysis of the guiding properties of ARROWs with a hollow core has been developed, for the first time to the authors' knowledge, in a wide wavelength range, between 600 *nm* and 900 *nm*. The field distribution, the dispersion curves and the confinement loss for both the TE and TM polarizations have been evaluated in water, as well as ethylene glycol filled rectangular core ARROW by applying a full-vector modal solver based on the FEM. Results have highlighted the differences due to the use of different liquid core material and allowed the transition from guided to surface mode in correspondence of the anti-crossing points of the dispersion curve to be described. The related confinement loss has been discussed as well, showing much lower CL levels for the ethylene glycol filled core and the TE polarization.

A further analysis on the effect of the core geometry, its dimension and the number of the cladding layers around the core will be done in future and also described at presentation time.

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