Large-Core Single-Mode Waveguides With Cross-Sectional Antiresonant Confinement

A. Llobera, I. Salinas, A. López, I. Garcés, C. Domínguez, and E. Lora-Tamayo

***Abstract*—This paper presents asingle-mode waveguide based in cross-sectional antiresonant confinement. The confinement in the vertical direction is obtained placing a Fabry–Pérot tuned at its antiresonant condition underneath the core [defining the antiresonant reflecting optical waveguides (ARROW) structure]. Small weightings are placed on both sides of the core to achieve a local increase in the effective refractive index, obtaining the so-called lateral antiresonant structures (LASs). They assure both the cross-sectional confinement and the single-mode behavior of the global structure. Simulations predict the transition of the symmetrical mode of the LAS to a bidimensional ARROW mode below the cutoff condition of the former, while at the cutoff condition of the asymmetrical LAS mode power is directly transferred to a radiative mode. Experimental results have shown that losses decrease as the lateral core width increases, which is in agreement with a minor confinement in the structure. Near-field images from a 3-μm-thick, 16 μm-wide ARROW-two-dimensional structure have shown that when a misalignment between the input optical fiber and the waveguide is produced, no higher order modes are excited, confirming the single-mode behavior of these structures.**

***Index Terms*—Antiresonant reflecting optical waveguides (ARROWs) structures, integrated optics, silicon technology, single-mode waveguides.**

I. Introduction

SINGLE-MODE optical waveguides on semiconductor substrates are the basic elements of integrated optical circuits due to the possibility of integrating several optical and electrical devices monolithically. Nowadays, waveguides based on total internal reflection (TIR) are broadly used due to the simplicity of its configuration. Nevertheless, to obtain a single-mode TIR waveguide, a low value for their normalized frequency is required [1], which, for a given wavelength, means a reduction of the core size or the use of small differences between the refractive indexes of the core and the surrounding layers. The reduction of the core size is a major drawback if light is injected by end-fire coupling using a single-mode optical fiber, since the mismatch between cross sections causes high insertion losses. As an example, the core of a silicon nitride waveguide surrounded by air working at $\lambda = 0.633$ nm should not exceed 0.1 μm if single-mode behavior has to be obtained. On the contrary, working with closer refractive indexes allows core thicknesses similar to these of the single-mode optical fiber, but they require thick buffer layers (especially if silicon is used as a substrate in the visible range) and an extremely good homogeneity of all layers, both in thickness and in refractive index.

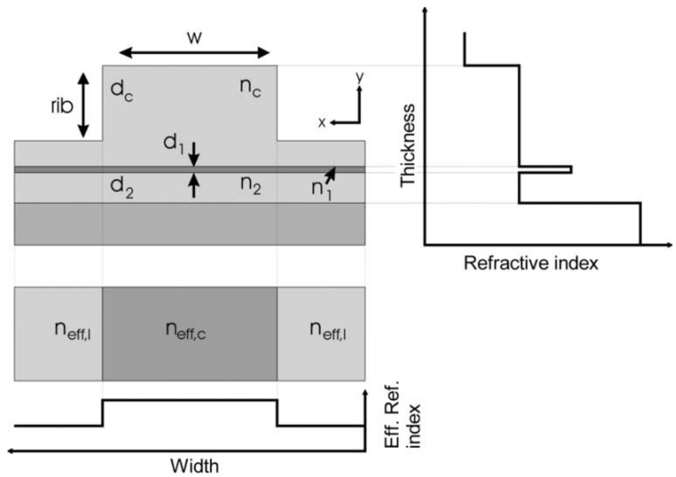

Fig. 1. Configuration and refractive-index profile of a rib-ARROW structure.

Unlike TIR waveguides, antiresonant reflecting optical waveguides (ARROWs) [2] confine the light in the lowest refractive-index layer by means of a Fabry–Pérot structure placed beneath the core, as shown in Fig. 1. For a given working wavelength and fixed refractive indexes of the layers, there exist some values for the first and second cladding layers (d_1 and d_2) where maximum reflection at the core-first cladding boundary is achieved ($> 99.96\%$) for the fundamental mode [3]. Higher order modes are filtered out since the antiresonant layers are not properly sintonized for them. Hence, this structure has single-mode behavior for core thicknesses similar to that of the optical fiber, minimizing the insertion losses.

Although ARROW structures provide a single-mode behavior in the Fabry–Pérot axis (the y axis in Fig. 1), the cross-sectional confinement required for most integrated optics devices is mainly achieved by making a rib on the core of the waveguide, as also shown in Fig. 1. Previously presented experimental results with 65% etching [4] have proven that ARROW waveguides wider than 7 μm support several lateral modes. This behavior can be understood using the basis of the effective-refractive-index method [5]: the partially etched zones have a lower effective refractive index ($n_{\mathrm{eff},l}$) as compared with the nonetched zone ($n_{\mathrm{eff},c}$). Then, the guiding structure

Manuscript received April 29, 2003; revised March 5, 2004. This work was supported in part by the Generalitat de Catalunya (Catalan council) under Grant 2001-TDOC-00008.

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Digital Object Identifier 10.1109/JLT.2004.829225

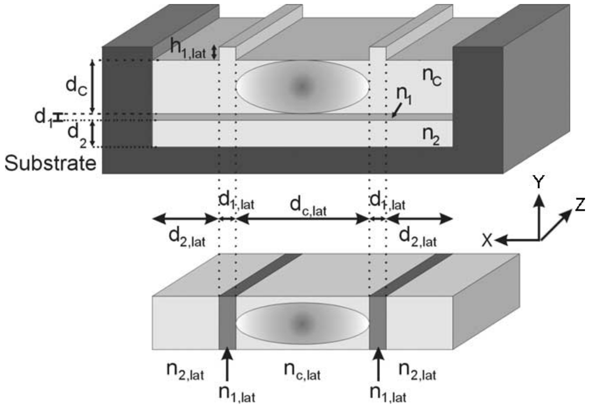


Fig. 2. ARROW-2D waveguide with single LAS and effective-refractive-index-equivalent slab structure. The thicknesses of the layers are $d_c = 3\ \mu$m, $d_1 = 0.35\ \mu$m, and $d_2 = 1.5\ \mu$m, while the refractive indexes are $n_c = 1.462\ \mu$m, $n_1 = 2.00\ \mu$m, and $n_2 = 1.46\ \mu$m.

behaves in the x axis as a standard waveguide with effective-refractive-index values. Thus, its lateral modal properties are still restricted to the conditions imposed by TIR guiding.

Confinement in the lateral direction (x axis) can also be obtained with strip ARROW structures, as was previously discussed for waveguides in [6] and [7] and for semiconductor lasers in [8]. In both cases, small structures were defined over the core of a slab TIR waveguide. Although this structure filters the higher order lateral modes, the number of modes in the y axis still depends on the core thickness. In this paper, the analysis and characterization of a modified ARROW structure (labeled ARROW-2D) with cross-sectional antiresonant confinement is presented. Its basic configuration is shown in Fig. 2. It consists on small weightings over the basic slab ARROW structure, which cause the appropriate changes in the effective index to emulate the first cladding of a lateral ARROW structure with effective-refractive-index values, and straightforwardly providing transversal confinement. A second cladding in the x axis is achieved by leaving a distance $d_{2,\mathrm{lat}} = d_{c,\mathrm{lat}}/2$ between the lateral first-cladding antiresonant structures (LASs) and the edges of the waveguide (made of silicon). The main advantage of these kinds of waveguides as compared with the previously described waveguides (TIR, ARROW, and strip-ARROW) is that the number of modes in the cross section depends on the design of both Fabry–Pérots, but not on the core dimensions. Thus, this configuration allows defining large-core single-mode waveguides with much lower insertion losses than standard silicon nitride TIR waveguides. Moreover, it is possible to place several LAS, forming multi-ARROW structures without causing high mechanical stresses, in contrast with the standard ARROW-C structures [3].

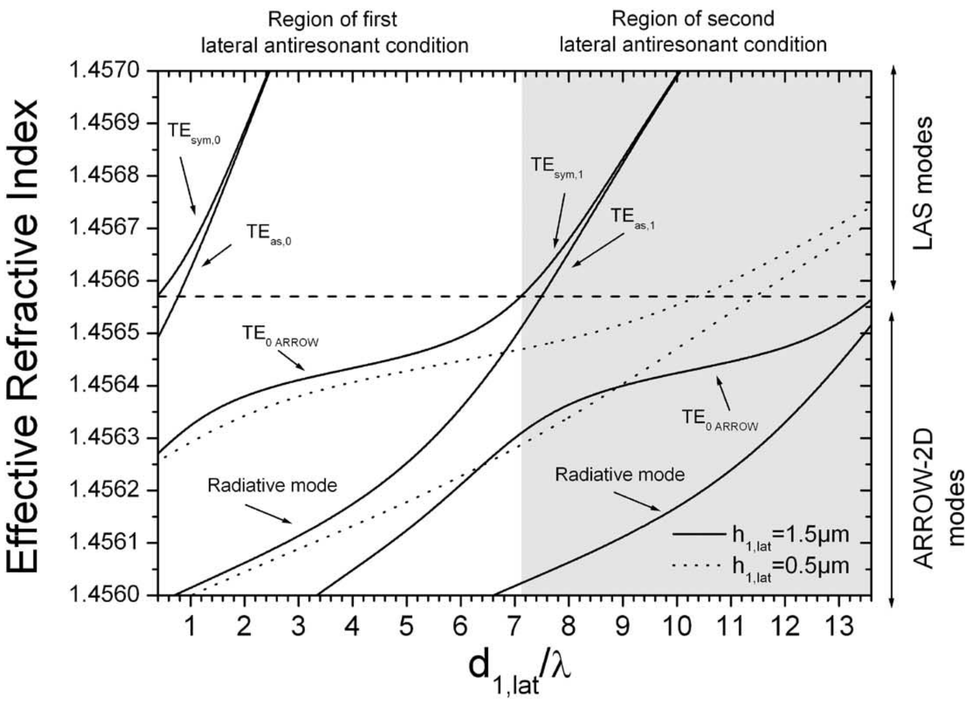
II. Simulation

Optimization of the ARROW-2D structure has been done using the nonuniform finite-difference method (NU-FDM) and the beam-propagation method (BPM), together with the effective-index method (EIM) to reduce the dimensions of the structure. Cross-sectional field amplitude profiles have been obtained using the finite-element program ANSYS 5.7.

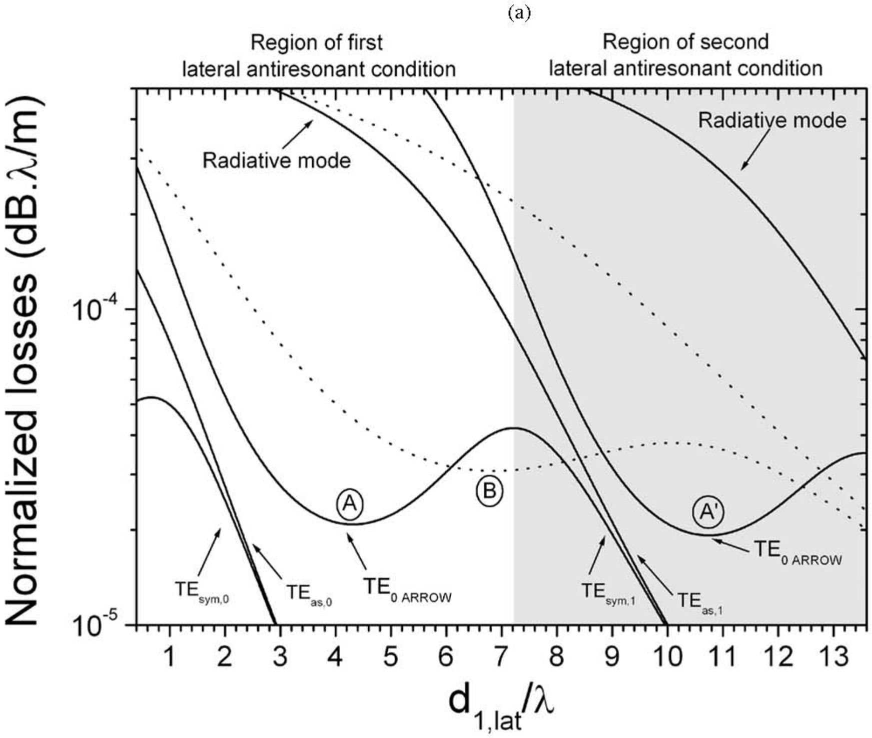
Since the behavior of the ARROW structure is well known [2], its dimensions and refractive indexes will be chosen to have maximum vertical confinement, that is, working with refractive indexes of $n_c = 1.462\ \mu$m, $n_1 = 2.00\ \mu$m, and $n_2 = 1.46\ \mu$m, together with a core thickness $d_c = 3\ \mu$m, the optimal dimensions for the first and second cladding layer are $d_1 = 0.35\ \mu$m and $d_2 = 1.5\ \mu$m, respectively. These thicknesses and refractive indexes will be considered as fixed throughout this paper. This configuration, known as an ARROW-A, is polarization selective, that is, transverse-electric (TE) modes have much lower losses than its transverse-magnetic (TM) counterparts. For this reason, this work will be restricted to the optimization of the LAS structures, in order to assure the maximum confinement on the TE modes on the waveguide.

Attenuation and dispersion (effective refractive index) results for two different values of $h_{1,\mathrm{lat}}$ (LAS height) as a function of the normalized LAS width $(d_{1,\mathrm{lat}}/\lambda)$ are shown in Fig. 3. As can be observed in Fig. 3(a), and in opposition to the previously reported behavior of the slab ARROW structure [3], the ARROW-2D structure supports two different types of lateral modes: 1) those confined in the small weightings with effective refractive indexes between $n_{c,\mathrm{lat}}$ and $n_{1,\mathrm{lat}}$: (LAS modes), labeled as $\mathrm{TE}_{\mathrm{sym},i}$ and $\mathrm{TE}_{\mathrm{as},i}$ (with $i = 0, 1, 2\ldots$), and 2) the modes confined in the large area core, which have effective refractive indexes lower than $n_{c,\mathrm{lat}}$. These ARROW-2D modes have been labeled as $\mathrm{TE}_{0,\mathrm{ARROW}}$, and these are the modes in which we are most interested. It should be noted that for a given configuration, both types of modes can propagate in the structure, and the actual field propagation will depend on the waveguide excitation characteristics. For the structure we are studying, the value of $n_{c,\mathrm{lat}}$ is 1.456 57. When the value of $d_{1,\mathrm{lat}}/\lambda$ decreases, the effective refractive index of the LAS modes also decreases until it goes below the value of $n_{c,\mathrm{lat}}$. At this point, the lateral structure cannot support a guided mode in the lateral direction, and the mode can only behave as an ARROW-2D mode.

Local minima of the normalized losses [Fig. 3(b)] are obtained when the first or second lateral antiresonant condition is fullfilled (points A and A', respectively). This lateral antiresonant condition means that the two LAS regions surrounding the core have a width that is an odd multiple of $\lambda_1/4$, with λ_1 being the projected wavelength [8]. At this point, it can be clearly observed that this waveguide has a single-mode behavior, since all the other modes correspond either to LAS modes or radiative modes. This latter point can be confirmed with the help of the Fig. 4: for values of $d_{1,\mathrm{lat}}/\lambda$ above cutoff condition, the field amplitude profile corresponds to the higher order modes (in this case, the $\mathrm{TE}_{\mathrm{sym},1}$ and $\mathrm{TE}_{\mathrm{as},1}$) of a rib directional coupler formed by the two LASs. When the cutoff condition is reached, the $\mathrm{TE}_{\mathrm{sym},1}$ is transferred to the ARROW-2D modes. On the contrary, it can be clearly observed in Fig. 3(b) and also in Fig. 4 that when the cutoff condition for the $\mathrm{TE}_{\mathrm{as},1}$ is reached, this mode cannot be supported by the structure, and it is transferred to a radiation mode, which has high losses and does not propagate through the waveguide. Hence, in ARROW-2D waveguides, similarly to the ARROW-A structures, two different modes can be observed. On one hand, there are the ARROW modes, in which we are interested. On the other hand,



(a)



(b)

Fig. 3. (a) Effective refractive index and (b) normalized losses of a 16-μm-wide, 3-μm-thick ARROW-2D structure working at 633 nm for two different LAS heights ($h_{1,\mathrm{lat}}$). Transition between the symmetrical mode of the LAS ($\mathrm{TE}_{\mathrm{sym},1}$) and the ARROW-2D mode ($\mathrm{TE}_{0,\mathrm{ARROW}}$) is observed at lateral antiresonant condition.

those belonging to the LAS structure (which would correspond to the high-index first antiresonant layer in the ARROW-A). It is noteworthy to mention that the $\mathrm{TE}_{\mathrm{sym},0}$ (which would correspond to the TE_0 when compared with the ARROW-A structure) is never cut off. Then, this mode could be excited by light coupled directly to the LAS structure. This result is expected, since the LAS structures have a higher effective refractive index than the surrounding media. Nevertheless, at the A (and also at A') working points, the LAS structures are in lateral antiresonance, which means that if the light is injected in the core of the ARROW-2D waveguides, it would experience ultrahigh reflection due to the LAS. Hence, no power would

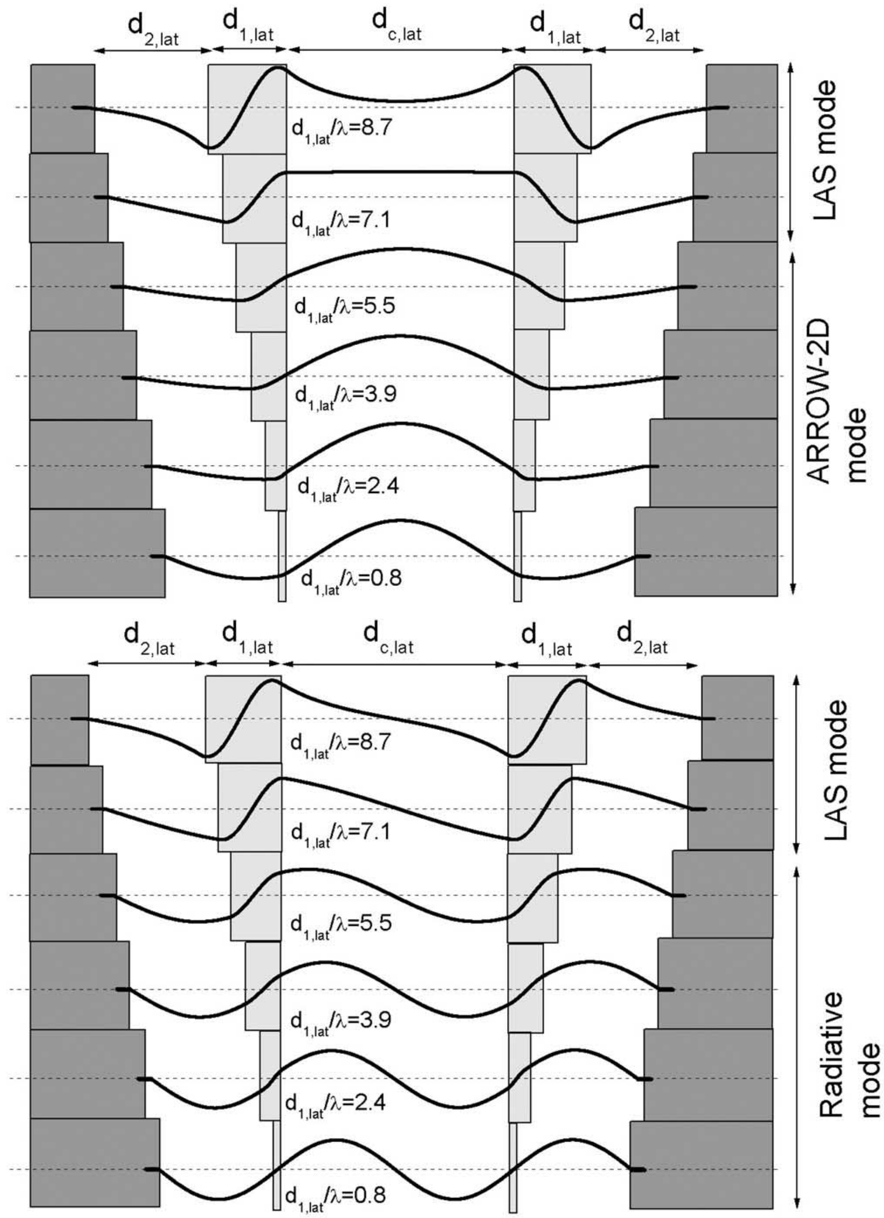


Fig. 4. Transformation of field profile of the $\mathrm{TE}_{\mathrm{sym},1}$ and $\mathrm{TE}_{\mathrm{as},1}$ as the $d_{1,\mathrm{lat}}/\lambda$ approaches the cutoff condition: symmetrical modes are transferred to the ARROW-2D modes, while asymmetrical modes are radiative modes below cutoff.

be transferred from the ARROW mode to the symmetrical and asymmetrical fundamental modes of the LAS structure at the lateral antiresonant conditions.

Finally, as $h_{1,\mathrm{lat}}$ (LAS height) increases, the antiresonant lateral regions become narrower and the minimum of the normalized losses at the antiresonant condition is reduced (point B in Fig. 3). These results are attributable to a stronger LAS with a higher effective-refractive-index difference between the core ($n_{c,\mathrm{lat}}$) and the LAS ($n_{1,\mathrm{lat}}$).

The field amplitude profiles shown in Fig. 5 belong to a 16-μm-wide ARROW-2D waveguide with the LAS optimized according to the previously presented results, that is, with $h_{1,\mathrm{lat}} = 1.5$ μm and $d_{1,\mathrm{lat}}/\lambda$ at its first antiresonant condition ($d_{1,\mathrm{lat}}/\lambda = 4.67$). As can be seen, there are only two types of modes, which correspond to (a) $\mathrm{TE}_{\mathrm{sym},0}$ and (b) $\mathrm{TE}_{\mathrm{as},0}$ modes of the LAS, together with (c) the ARROW-2D mode. Then, from the previous simulations, it can be concluded that the proposed ARROW-2D configuration will have single-mode behavior with core dimensions of 3×16 μm, much larger than any previously reported single-mode waveguide. Fig. 4(d) shows the same ARROW-2D structure but with two LAS on each side of the core. This modification causes the expected enhancement of the confinement in the waveguide core.

III. Fabrication and Characterization

Ten ARROW-2D structures of a length of 6000 μm were fabricated with core widths ranging from 10 to 40 μm (with the LAS optimized for each width). Five of these structures have one LAS on each side of the core, while in the other five, two LASs were placed on each side. The fabrication of the ARROW-2D structures started with the definition of the

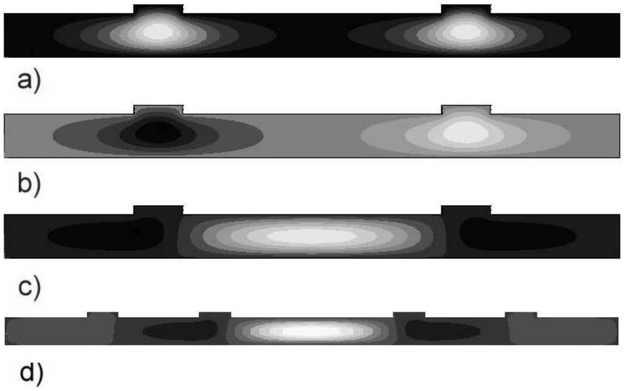


Fig. 5. Cross-sectional electric-field profiles of an ARROW 2-D structure with LAS structure at its first antiresonant condition $(d_{1,\mathrm{lat}}/\lambda = 4.67)$: (a) $\mathrm{TE}_{\mathrm{sym},0}$, (b) $\mathrm{TE}_{\mathrm{as},0}$, (c) ARROW-2D mode, and (d) ARROW-2D mode in an ARROW-2D structure with double LAS.

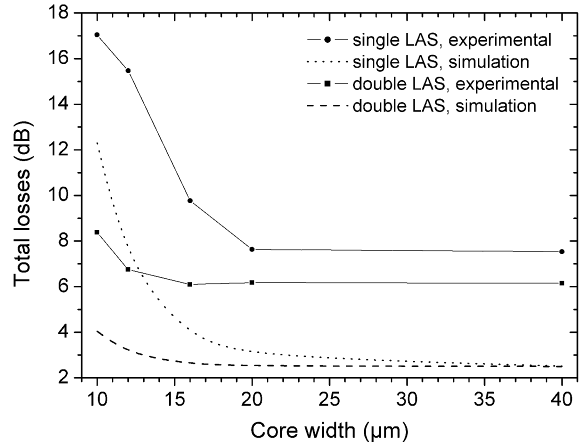


Fig. 6. Experimental and simulated losses as a function of the waveguide width $(d_{c,\mathrm{lat}})$ for ARROW-2D structures with single and double LAS.

trenches where they would be located. Then, a thin silicon dioxide (0.2 μm) was grown on the silicon substrate, and the first photolithographic step was done. At this point, a dry silicon oxide etch opened the windows on the SiO_2. After the silicon dry-etching step that defined the trenches, wafers were submerged in HF (49%) so as to remove the remaining silicon oxide mask.

Once the micromechanized silicon has been finished, the slab ARROW structure is fabricated, with 2.0-μm silicon dioxide ($n = 1.46$ at 633 nm), 0.35-μm silicon nitride ($n = 2.00$ at 633 nm) and 4.5-μm PECVD silicon oxide ($n = 1.462$ at 633 nm) layers, which are sequentially obtained. After the second mask and a silicon oxide dry etching of 1.5 μm, the LASs are defined.

Light from a superluminescent light-emitting diode (SLED) working at 678 nm was injected to each ARROW-2D by end-fire coupling using a single-mode optical fiber. The output power was collected by a multimode optical fiber with a core diameter of 50 μm. Results for the losses versus the core width $(d_{c,\mathrm{lat}})$ are presented in Fig. 6. It can be clearly observed that experimental and simulation data show the same behavior, which also matches with that of the previously reported rib-ARROW waveguides [4] The increase of losses as the core gets narrower is due to a decrease of light confinement into the waveguides. This assumption is confirmed when comparing the results obtained for waveguides with single and double LAS: for a given $d_{c,\mathrm{lat}}$, losses are significantly lower in the latter case. Moreover, the width value at which losses sharply increase is also lower for waveguides with double LAS. Finally, total losses are independent of $d_{c,\mathrm{lat}}$ for values above 20 μm, since its value is 7.53 and 6.14 dB for single and double lateral antiresonant structures, respectively. The difference between experimental and simulation results can be attributed to the presence of impurities or inhomogeneity on the core layer, which may cause a deviation on the effective refractive indexes and, straightforwardly, a deviation from the optimal conditions for the lateral confinement, thereby increasing the lateral losses.

Although these previous results provide a confirmation for the behavior of the ARROW-2D waveguides, the primary objective of their design was to obtain large-core single-mode waveguides. To analyze its modal properties, near-field images were

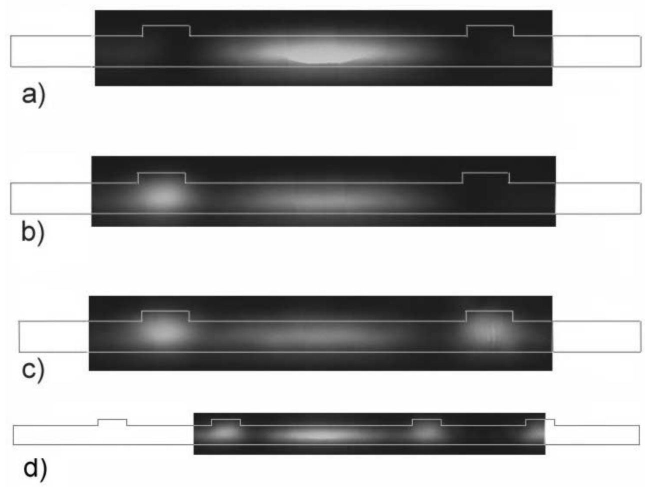


Fig. 7. Near-field images of ARROW-2D structures. (a) Centered injection with single LAS. (b) Lateral injection with single LAS. (c) Broad injection with single LAS. (d) Centered injection with double LAS. (e) Lateral injection with double LAS. (f) Broad injection with double LAS.

taken from the ARROW-2D waveguides with single and double LAS. First of all, a single-mode optical fiber was aligned at the center of the waveguide, whose output intensity profile was obtained. Then, the input fiber was progressively misaligned to determine whether it was possible to excite any higher order mode apart from those of the LAS. Finally, the fiber was placed again at the center of the waveguide, but this time a larger distance was left between the optical fiber and the waveguide. Thus, the input field was broad enough to inject light into the LAS and the waveguide simultaneously, which allowed information to be obtained concerning the relative intensity between the modes of the whole structure.

The near-field profiles of ARROW-2D waveguides with single LAS are shown in Fig. 7(a)–(c). The $\mathrm{TE}_{0,\mathrm{ARROW}}$ mode is excited when light is coupled into the waveguide. As the optical fiber is progressively misaligned, the fundamental mode decreases in amplitude but does not vary its shape, thus confirming the single-mode behavior of ARROW-2D waveguides. If light is injected in the whole structure, power coupled into the lateral antiresonant structures is higher than into the core, as predicted by simulations. On the contrary, near-field profiles of ARROW-2D waveguides with double LAS [Fig. 7(d)] have the same modal properties as the structure with single LAS, but in this case, power propagating through the core is higher than that in the LAS structures. This point is in agreement with the higher confinement expected for the ARROW-2D structures with double LAS.

Near-field results confirm that only with broad coupling or fiber-waveguide misalignment is it possible to excite the LAS modes. Both points are in agreement with a direct light injection to the LAS structure. On the contrary, when the light is only injected at the core, no light is transferred to these structures, confirming the previously discussed assumptions.

IV. Conclusion

The basis for a large-core single-mode waveguide based on antiresonant confinement has been presented. Rib has been replaced in ARROW waveguides by LAS which increase the effective refractive index to obtain the lateral antiresonant confinement. Simulations have predicted the coexistence of ARROW-2D modes and LAS modes in these waveguides. Below the cutoff condition, the $\mathrm{TE}_{\mathrm{sym},i}$ is transferred to the ARROW-2D mode, while the $\mathrm{TE}_{\mathrm{as},i}$ is not supported by the structure and is converted into a high-loss radiative mode. Simulations predict single-mode behavior of a waveguide with a 16-μm-wide, 3-μm-thick core. Experimental measurements of the total losses as a function of the core width with single and double LAS match the behavior predicted by simulations and show that double LAS provides better confinement than single LAS, together with a decrease of the losses as core width increases. Finally, near-field images have shown that a misalignment between the center of the waveguide and the input optical fiber does not excite higher order modes, thus confirming the single-mode behavior of the ARROW-2D structure.

Acknowledgment

The authors would like to thank the Generalitat de Catalunya (Catalan Council) for its support.

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