Liquid crystal-based dielectric loaded surface plasmon polariton optical switches

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An optical switch based on liquid crystal dielectric loaded surface plasmon polariton waveguides is proposed and theoretically analyzed. The infiltration of the plasmonic structure with a nematic liquid crystalline material serving as the dielectric loading is shown to allow for extensive electrical tuning of its waveguiding characteristics. Both the electrical switching and optical properties of the proposed waveguide are investigated in the context of designing a directional coupler optical switch, which is found to combine efficient voltage control, low power consumption, high extinction ratio, and relatively low insertion losses. © 2011 American Institute of Physics. [doi:10.1063/1.3658247]

I. INTRODUCTION

Intensive investigation is being conducted in the field of guided-wave plasmonics ever since the acknowledgment that the manipulation and routing of the strongly localized surface plasmon polaritons (SPPs) can lead to the realization of reduced physical scale photonic devices. SPPs are surface electromagnetic waves, sustained by coherent electron oscillations in a metal/dielectric interface. Light propagation in plasmonic waveguides combines the unique property of sub-wavelength confinement beyond the diffraction limit, along with the large bandwidth associated with photonics.

To date, a variety of plasmonic structures has been shown capable of confining and guiding SPP modes. These include stripe, slot, and channel waveguides as well as the other designs as presented in Refs. 1–3. Among these, the dielectric loaded surface plasmon polariton (DLSPP) waveguide offers some distinctive advantages4 and has been employed in numerous passive wavelength-selective optical components.5–9 In particular, DLSPP waveguides are capable of providing strong confinement in both transverse directions and permit the design of low-loss bend elements, while keeping overall propagation losses relatively low. Moreover, by thermally tuning the refractive index of the dielectric material used as loading, active components can be implemented. Tunable add-drop filters and Mach-Zehnder interferometers, which permit external control and offer a high level of functionality have already been demonstrated.10–12

The aforementioned waveguides are loaded by the commonly used low index polymer poly(methyl methacrylate) (PMMA). PMMA could alternatively be substituted by a low index dielectric material found, for instance, among fluidic solutions, widely used in the optofluidic industry. These solutions have proven to effectively facilitate optical confinement in solid planar waveguides and fibers, photonic crystal structures and other implementations as presented in Refs. 13 and 14. Among the most common optofluidic configurations stand structures infiltrated by the inherently anisotropic nematic liquid-crystals. Due to their unique aspect of providing controllable birefringence, liquid crystal components are proposed as switches, couplers, and filters in various applications.15–18

This study focuses on the analysis and design of liquid crystal-based DLSPP (LC-DLSPP) elements, and the implementation of an electrically tunable LC-DLSPP optical switch for the 1.55 μm telecom window. The proposed LC-DLSPP waveguide consists of a thin Au film loaded by PMMA. The polymer is etched in order to form a channel, which is then infiltrated by the common nematic material E7. An indium tin oxide (ITO) electrode is placed above the main guiding region, permitting the application of an external voltage, while the Au film serves as the ground layer. By controlling the molecular orientation of the LC via the applied field, the effective index of the fundamental TM00 mode can be tuned in an extensive range. Thus, the proposed LC-DLSPP structures combine all the attractive properties of conventional DLSPP waveguides, along with high tunability at low operating voltage values, which is significantly enhanced compared to thermally tunable components based on the thermo-optic effect. Moreover, as electrical LC-tuning involves capacitive operation, power consumption is reduced by orders of magnitude, a feature shared by all LC-based optical devices.19

To demonstrate the advantages of LC-DLSPP structures, a directional coupler switch comprising such waveguides LC-DLSPP waveguides is thoroughly analyzed. Efficient switching operation is demonstrated, at low operating voltages, high extinction ratio, and sufficiently low coupling...
lengths. The proposed devices are envisaged as key elements in plasmonics-based photonic integrated circuits for the ample control and routing of optical signals.

The paper is organized into 6 sections. Following the Introduction, Sec. II presents the analysis of the switching of nematic materials infiltrating channel DLSPP waveguides. Their optical properties are investigated in Sec. III. Section IV addresses the tuning and optical properties of a directional coupler formed by two LC-DLSPP waveguides, while Sec. V demonstrates voltage-controlled switching operation based on the proposed coupler. Finally, conclusions are discussed in Sec. VI.

II. LC-SWITCHING IN INFILTRATED DLSPP STRUCTURES

The LC-DLSPP elements investigated in the present study are based on the fundamental layout shown in Fig. 1. A 100 nm layer of gold is deposited upon a silica glass substrate. Next, a PMMA polymer layer of height \( h \) is spin-coated on the metal stripe, and subsequently etched to form a channel of width \( w \), which is infiltrated by the nematic LC-compound material E7. The structure is sealed on top by an optical layer followed by ITO electrode and a superstrate. The optical and electrical properties of the buffer layer (height \( h_b \)) match those of silica glass. The selection of the above materials (i.e., PMMA and E7) is preferable as both are very well studied (in terms of optical and physical properties) and substantial fabrication expertise is available. In addition, both are commonly used in plasmonics and LC photonics operating at the 1.55 \( \mu \)m window.

A low-frequency voltage of varying value is applied at the ITO electrode, the electrical path terminating at the grounded metal film. The electric field induces a reorientation of the LC molecules, which tend to align with the applied field, modifying the overall electrical and subsequently optical properties of the LC material. The exact profile of the molecular orientation and the extent of the LC-switching depend on the value of the applied voltage, the molecular anchoring conditions at the channel’s walls, the geometry of the structure, and the material properties of the LC and the surrounding isotropic materials, PMMA and silica in this case. The static permittivity of the E7 is characterized by a parallel component of \( \varepsilon_{||} = 18.6 \) and a perpendicular of \( \varepsilon_{\perp} = 5.3 \), and its elastic constants \( K_{11}, K_{22}, \) and \( K_{13} \), are taken equal to 10.3 pN, 7.4 pN, and 16.48 pN, respectively.\(^{20}\) PMMAs relative dielectric constant at low frequencies is equal to 2.6, while that of silica is equal to 3.91. The accurate calculation of the LC molecular reorientation profile requires the solution of the coupled electrostatic/elastic problem, which involves the minimization of the total energy of the system, as described in detail in Refs. 21 and 22. The resulting set of partial differential equations is solved via a commercially available finite element method solver-based PDE solver.\(^{23}\)

In the absence of an applied field, the alignment of the nematic material depends primarily on the anchoring conditions at the LC/material interfaces. As far as, the LC/metal interface is concerned, Au is found to provide homogeneous alignment.\(^{24}\) At the LC/polymer interface, PMMA provides planar degenerated alignment,\(^{25}\) while various techniques enable control over the polar and azimuthal anchoring energies.\(^{26}\) In any case, none of the LC/material interfaces involved in the proposed structures has been shown to promote homeotropic anchoring conditions. In our analysis, we assume strong homogeneous anchoring conditions, that is, the LC-molecules are aligned with the \( z \)-axis at the channel’s walls at the absence of any electric field. Such an orientation may be efficiently enforced by introducing alignment layers at the LC/metal,\(^ {27}\) LC/glass, or LC/PMMA interfaces. The local orientation of the nematic LC is described by the nematic director, which for the \( z \)-invariant geometry under study is defined as

\[
\mathbf{n} = n_x \hat{x}_0 + n_y \hat{y}_0 + n_z \hat{z}_0, \\
= \cos \theta \sin \phi \hat{x}_0 + \sin \theta \hat{y}_0 + \cos \theta \cos \phi \hat{z}_0, 
\]

with \( \theta(x, y) \) and \( \phi(x, y) \) expressing the tilt and twist angles as depicted in Fig. 1(c). In the absence of the electric field that is when the liquid crystal is at the rest state as shown in Fig. 1(a), all LC-molecules lie in parallel to the \( z \)-axis and the angles \( \theta \) and \( \phi \) are equal to zero.

The application via the ITO layer of a voltage above a certain threshold value induces the switching of the LC molecules, as schematically shown in Fig. 1(b). While the reorientation of the molecules adjacent to the side walls of the channel is restricted by the strong anchoring conditions, the molecules in the bulk area close to the channel’s axis are further switched as the intensity of the applied field increases. The profiles of the tilt and twist angles as well as the electric field lines for a voltage \( V = 2 \, V \), just above the threshold value, and \( V = 4 \, V \) are shown in Fig. 2. The electric field is perpendicular to the conducting ITO and Au layers, while at the lateral edges of the computational windows, Neumann boundary conditions for the electrostatic potential are applied. The total width of the computational window was set equal to 8 \( \mu \)m, that is, much larger than the width of the LC-channel. As the applied voltage increases, tilt and twist angles obtain higher values, with tilt being significantly more

![Fig. 1. (Color online) Schematic layout of the proposed LC-based DLSPP waveguide and principle of switching operation: (a) in the absence of an applied voltage (rest-case), the LC molecules lie along the axis of the channel; (b) when the applied voltage rises above a threshold value \( V > V_{th} \), the LC is switched; (c) tilt (\( \theta \)) and twist (\( \phi \)) angle definition for the nematic director \( \mathbf{n} \) and geometrical/material parameters of the structure.](image-url)
affected, since the LC molecules tend to align with the electric field. The profiles of both the angles are characterized by vertical symmetry (tilt is symmetric and twist is antisymmetric) with respect to the middle of the LC-channel, following the symmetry of the structure. The horizontal asymmetry observed mostly in the twist profile results from the deviation of the electric field lines at the interfaces between different dielectric materials. For sufficiently high voltage values, the LC is considered to be fully switched, the nematic director of the material tends to align in parallel to the y-axis and the tilt angle in the bulk LC area approximates 90°.

The switching efficiency of the structure with respect to a large range of applied voltage values is qualitatively presented in Fig. 3. The switching factor \( f \) is defined as the mean value of the local nematic director’s projection over the y-axis, that is, \( \mathbf{n} \cdot \mathbf{y}_0 = \sin \theta \), calculated over the LC-channel cross-section. The value of the threshold voltage above which the LC begins to switch is approximately equal to \( V_{th} = 1.8 \) V. For voltage values in the range of 1.8–10 V, the switching of the nematic material is particularly intense. As the voltage is further increased, the LC molecules are fully switched in the bulk region and their overall response is limited owing to the strong boundary conditions at the channel’s wall.

III. OPTICAL PROPERTIES OF LC-DLSPP WAVEGUIDES

Having investigated the LC-switching characteristics of the proposed structure, the analysis is extended to the study of the optical properties of the LC-DLSPP waveguide. The electrostatic analysis presented in Sec. II yields the profile of the relative optical permittivity tensor \( \epsilon_r \) in the LC-infiltrated channel, which along with the other material parameters is imported in a fully anisotropic finite element eigenmode solver.\(^\text{28-29}\) At the spectral window centered at 1.55 \( \mu \)m, the ordinary and extraordinary indices of E7 are \( n_o = 1.5024 \) and \( n_e = 1.6973 \).\(^\text{30}\) The Au film is a highly dispersive material and at 1.55 \( \mu \)m, it is characterized by a refractive index of \( n = 0.55 - j1.54 \).\(^\text{31}\) The refractive index of the optical buffer matches that of silica glass, \( n_b = 1.44 \), while PMMAs refractive index is considered to be equal to \( n = 1.49 \).

As observed in the layout of Fig. 1, the infiltrated LC-channel corresponds to a cross-section of \( w \times h \). As the selection of the channel’s dimensions is expected to have a direct impact on the optical properties of the LC-DLSPP waveguide, various structural designs have been investigated. Compatible to standard existing lithographic techniques, micron-sized waveguides can be readily manufactured and, moreover, allow for the infiltration of the channel by the LC-nematic material. The DLSPP fundamental TM\(_{00}\) mode is characterized by strong localization at the metal interface and thus the most crucial dimension influencing the modal properties is the width of the channel. In our analysis, the channel’s height is kept fixed at \( h = 1.0 \) \( \mu \)m and complying with the aspect ratios found to be optimal in the classical DLSPP configurations, different \( w \) values between 0.8 \( \mu \)m and 0.9 \( \mu \)m are investigated. Another important parameter to be taken into account is the presence of the ITO layer, which is characterized by a complex refractive index of \( n = 1.27 - 0.12j \) at 1.55 \( \mu \)m,\(^\text{32}\) as it may introduce a considerable amount of additional resistive losses. To minimize such losses, an optical buffer is introduced between the LC-channel and the ITO layer. Simulations indicate that a buffer layer of \( h_b = 500 \) nm is sufficient to optically isolate the ITO electrode from the guiding area.

The modal properties of the LC-DLSPP waveguide for \( h = 1.0 \) \( \mu \)m and \( w = 0.8, 0.85, \) and 0.9 \( \mu \)m have been calculated for voltage values varying from 0 to 20 V. Figure 4(a) presents the effective index of the fundamental TM\(_{00}\) mode for the three cases studied. As voltage rises and switching becomes more intense, the tilt angle obtains higher values and therefore the effective refractive index experienced by the y-polarized DLSPP mode rises as well. This leads to a progressive enhancement of light confinement and an increase of the modal effective index. Comparing the dispersion curves of the three waveguides, it can be observed that the waveguide of \( w = 0.9 \) \( \mu \)m offers a larger dynamic range of \( \Delta n_{\text{eff}} = n_{\text{eff}}(V_{\text{peak}}) - n_{\text{eff}}(V_{\text{th}}) \), implying greater potential functionality in the context of designing tunable optical plasmonic components. Additionally, simulations have indicated that among the three structures, the waveguide of \( w = 0.9 \) \( \mu \)m mostly favors optical confinement, which renders this selection as the most favorable with respect to the design of the LC-channel. Although further investigation with respect to the structural dimensions is possible via the same analysis, as it will be shown, the selection here made is suitable in terms of demonstrating all the salient features of the proposed LC-DLSPP elements.

![FIG. 2. (Color online) (a) Electric field lines and profile of (b) tilt and (c) twist angle for voltage values of \( V = 2 \) V and \( V = 4 \) V. The dimensions of the waveguide are taken equal to \( h = 1.0 \mu m \) and \( w = 0.9 \mu m \), while the height of the optical buffer is \( h_b = 500 \) nm. Only a fraction of the computational window, which extends to 8 \( \mu m \), is shown.](Image)

![FIG. 3. (Color online) Switching factor \( f \) for a waveguide of \( h = 1.0 \mu m \), \( w = 0.9 \mu m \), and voltage values varying from 0 to 20 V.](Image)
Given the small index contrast \( n_\text{m} \), losses are kept relatively low, with a propagation length \( L_p \) of around 63 \( \mu \)m. While a minimization of the losses is observed at \( V = 5 \) V. As the voltage initially rises, the LC-molecules occupying the region around the channel’s axis are tilted, enhancing light confinement in this core region, away from the lossy metal film, and subsequently losses are reduced (Fig. 2). Nevertheless, when voltage is further increased, the LC-molecules obtain a more uniform profile all over the channel’s cross-section, and the part of optical power confined close to the LC/metal interface is raised, resulting in higher losses and, therefore, lower values of \( L_p \).

### IV. Properties of Directional Couplers Based on LC-DLSPP Waveguides

The LC-DLSPP waveguide investigated in Sec. III can serve as the basic component in more complex devices such as the directional coupler presented in Fig. 5. Two identical waveguides, referred to as WG1 and WG2, of width \( w = 0.9 \) \( \mu \)m and height \( h = 1.0 \) \( \mu \)m, are formed on a grounded Au stripe, with the distance between them denoted as \( L_{\text{gap}} \).

Two coplanar electrodes are deposited on the top side of the optical buffer with a separation of 300 nm, a distance which is considered capable of reconciling the demand on minimized dimensions, independency of each electrode’s electric field and the limitations of the manufacturing process. At the two electrodes voltages of different variable values \( V_1 \) and \( V_2 \) may be applied, aiming to control the electrical and optical properties of the coupler. Optical power coupling between the two LC-DLSPP channel waveguides depends on the distance \( L_{\text{gap}} \) and their effective modal indices. In the present study, having as a reference, the results for the single LC-DLSPP waveguide presented in Fig. 4(a), we choose to keep hereinafter the voltage of the first electrode \( V_1 \) fixed at 4 V. This selection choice, on the one hand, ensures that the mode in WG1 is sufficiently confined and on the other hand, it offers the possibility to exploit a wide dynamical range of \( \Delta n_{\text{eff}} \) in the second LC-channel (WG2) by tuning the voltage \( V_2 \) of the second electrode.

The investigation of the structure begins by addressing the coupled electrostatic/elastic problem. Contrary to the case of the individual LC-infiltrated channel studied in Sec. II, the presence of both waveguides, characterized by their separation \( L_{\text{gap}} \), is expected to influence their LC-switching properties. In order to analyze the electrostatic problem of the coupled waveguide structure and to comment on the influence of \( L_{\text{gap}} \) on the reorientation of the nematic LC-material in each waveguide, two distinctive cases corresponding to \( L_{\text{gap}} = 300 \) nm and \( L_{\text{gap}} = 1300 \) nm are investigated.

Figure 6 shows the profiles of the tilt and twist angles for two structures of \( L_{\text{gap}} = 300 \) nm and \( L_{\text{gap}} = 1300 \) nm when the applied voltages are \( V_2 = V_1 = 4 \) V and \( V_2 = 2V_1 = 8 \) V, respectively. As expected, when the voltages \( V_1 \) and \( V_2 \) are equal, the LC-switching angle profiles are symmetrical with respect to the y axis at the center of the structure. When the LC-channel separation is \( L_{\text{gap}} = 1300 \) nm, Figure 6(a) shows that the tilt and twist angles profile are almost identical to those calculated in the single LC-channel case as presented in

![Image](https://via.placeholder.com/150)

**FIG. 5.** (Color online) Schematic layout of the proposed LC-DLSPP directional coupler.
Fig. 2. When different voltage values, $V_1 = 4\, V$ and $V_2 = 8\, V$, are applied to the electrodes, the second LC-channel exhibits higher tuning without notably affecting the LC-profile in WG$_1$. Thus, in this case, the separation $L_{\text{gap}}$ between the two channels is such that the LC-switching in each channel is similar to the equivalent problem of the individual channel. This behavior is anticipated, since both the LC-channels are laterally surrounded by an extensive PMMA region, as in the case of the single LC-channel, and they are situated far from the corresponding adjacent electrode.

On the contrary, when the two channels approach such that $L_{\text{gap}} = 300\, \text{nm}$, the LC-profile in each channel is influenced by the electric field of the adjacent electrode. As noticed in Fig. 6(b), the twist profile, particularly, does not exhibit any vertical symmetry, since the electric field in the region between the two channels is distorted with respect to the single waveguide case. This is more profoundly observed when higher voltage values are used, as in the case where $V_1 = 4\, V$ and $V_2 = 8\, V$. The deformation of the profiles is higher on the LC-channel's interior wall, that is, the area neighboring the adjacent LC-channel and electrode. The asymmetries observed are attributed to the fact that a part of the electric field lines corresponding to the adjacent electrode pass through the first LC-channel and distort the nematic director orientation.

Further information on the switching properties of the coupled LC-channels is provided in Fig. 7, where the switching factor for the structure of the two LC-channels is calculated in each channel for a voltage $V_2$ varying from 0 to 20 V, with $V_1$ fixed at 4 V. When the gap between the two LC-channels is large, the values of the switching factor in each LC-channel are only slightly influenced by the presence of the adjacent waveguide, while in the case where the gap becomes smaller the switching in the two individual LC-channels becomes more interdependent. Nevertheless, it should be underlined at this point, that despite the interdependence of the system of the two LC-channels, for the $L_{\text{gap}}$ values studied in this paper, the levels of the switching factor in each channel are different and mostly controlled by the corresponding electrode. In terms of optical properties, this implies that the structure is capable of providing two LC-channel waveguides of controllably distinct modal effective indices.

Various computational methods may be used to numerically analyze the propagation of surface plasmon polaritons in order to assess the light waveguiding properties of plasmonics-based structures. In the present study, the optical studies of the LC-DLSPP coupler are calculated by means of a 3-D finite-difference time-domain (FDTD) method that can handle arbitrary anisotropic materials and is also capable of dealing with dispersive media. However, before a rigorous numerical investigation of light propagation and coupling in the proposed structures is performed, some basic design outlines are provided via an approach based on the coupled mode theory (CMT). Coupled mode theory is only valid for weakly coupled waveguides and at this point of the analysis, the results provided may only be perceived as indicative of the structure’s performance. However, after completing the results of the rigorous full wave numerical analysis presented in Sec. V, it is verified that the two methods stand in fair agreement. According to the CMT formulation, the field in the coupler can be expressed as a linear combination of the two individual waveguide modes

$$E_{y}(x, y, z) = A_1(z)E_1(x, y)e^{-j\beta_1 z} + A_2(z)E_2(x, y)e^{-j\beta_2 z}, \quad (2)$$

where $A_1(z)$ and $A_2(z)$ express the local amplitude of the field in each LC-channel waveguide. The propagation constants $\beta_i$ and the electric field spatial transversal profiles $E_i(x, y)$ refer to the modes supported by each individual LC-channel that is assuming an infinite separation between them. Given that the coupling coefficients do not depend on $z$, as the structure is $z$-invariant, and that the modes propagate along the same direction, the amplitude of the field in each waveguide of the structure can be described by

$$\frac{dA_1}{dz} + jkA_2e^{-j\Delta\beta z} = 0,$$

$$\frac{dA_2}{dz} + jkA_1e^{+j\Delta\beta z} = 0,$$ \quad (3)
with $\kappa$ being the coupling coefficient and $\Delta \beta = \beta_2 - \beta_1$. Coupling between the two modes is highly dependent on the distance $L_{\text{gap}}$, the closer the waveguides, the stronger the coupling between them.

When voltage of the same value is applied on both electrodes ($V_1 = V_2$), the two waveguides are identical ($\Delta \beta = 0$), and optical power is fully exchanged between them along the propagation distance with a period $L_c$. This state is referred to as synchronous and $L_c$ is the coupling length of the structure. The power exchange in the synchronous case can be interpreted in terms of supermode excitation. Supermodes express field profiles that extend in both waveguide cross-sections and are characterized by a global propagation constant. Figure 8 presents a comparison between the effective index dispersion curves of the structure’s supermodes and those of the individual waveguides, with respect to the voltage $V_2$ at the operational wavelength of 1.55 $\mu$m, with $V_1 = 4$ V. The individual modes are calculated by solving the eigenmode problem in each LC-channel, using the nematic director profiles derived from the solution of the electrostatic problem in the coupled structure. The effective index of the individual mode 1 in the voltage fixed LC-channel WG1 is slightly influenced by the voltage $V_2$ due to the aforementioned interdependency between the LC-channels electrical switching properties. The refractive index of individual mode 2 increases as voltage $V_2$ obtains higher values. Supermodes are calculated by solving the coupled eigenmode problem in the coupler structure, which comprises both LC-channels. The supermode of the highest refractive index is defined as supermode 1. Starting at the point $V_2 = 2$ V, it is observed that the individual mode of WG1 is characterized by a higher effective index and it almost coincides with the effective index of supermode 1. As voltage $V_2$ increases, supermode 1 evolves from individual modes 1 to 2, the opposite being the case for supermode 2. When $V_1 = V_2 = 4$ V, the two LC-channels are synchronous and the effective indices of the individual modes 1 and 2 are equal (point S in Fig. 8). At this state, the two supermodes are characterized by a symmetric and antisymmetric amplitude profile ($A_1 = \pm A_2$) in the two LC-channels, respectively. In this case, optical power propagating through the waveguides is characterized by a beating phenomenon. The coupling length $L_c$ at which complete power exchange occurs is a function of the difference between the propagation constants of the symmetric ($\beta_s$) and antisymmetric ($\beta_a$) supermode at the synchronized state and is equal to $L_c = \pi/|\beta_s - \beta_a|$. Constants $\beta_s$ and $\beta_a$ depend on the switching of the nematic material and the distance $L_{\text{gap}}$ between the LC-channels.

Keeping the electrodes voltages fixed at $V_1 = V_2 = 4$ V, the coupling length $L_c$ may be set by adjusting the distance $L_{\text{gap}}$. The limitations to be taken into consideration at this point are that the coupling length should be sufficiently small compared to the propagation length and that the distance $L_{\text{gap}}$ should be equal or larger that the electrodes distance. Structures of $L_{\text{gap}}$ within the range of 300 nm to 700 nm have been investigated and the corresponding coupling lengths at 1.55 $\mu$m are presented in Table I. In all cases, coupling length ranges from 20 to 40 $\mu$m, while the propagation length is of the order of 63 $\mu$m.

When voltage $V_2$ rises mode confinement in WG2 is enhanced and the LC-DLSSP waveguides become mismatched ($\Delta \beta \neq 0$). At this state, the coupling between the two LC-channels degrades; nevertheless, the beating phenomenon is still present, but only a fraction of the propagating power may be coupled to the adjacent waveguide. The maximum coupled power scales with $\kappa^2/\left(\kappa^2 + \Delta \beta^2\right)$, while the period of the exchange scales with $\sin^2\left(\sqrt{\kappa^2 + \Delta \beta^2}\right)$. The increase in the phase-mismatch term outperforms the decrease of the coupling term resulting in faster power exchange (which is equivalent to a shorter periodicity). Finally, for high levels of phase-mismatch, the exchanged power becomes negligible. According to CMT, when the mismatch between the propagation constants of the individual waveguides WG1 and WG2 obtains the critical value $\Delta \beta^2 = 3\pi/L_c$, power coupling between the two waveguides at a propagation distance equal to $L_c$ is minimized. This state of operation of the directional coupler is referred to as asynchronous, and the values of the critical mismatch $\Delta \beta_{\text{cr}}^2 = \Delta \beta_{\text{cr}}^2/\kappa_0$ at 1.55 $\mu$m corresponding to each value of $L_{\text{gap}}$ are reported in Table I along with the coupling parameters. Table I includes the maximum refractive index difference of the two LC-channels at 1.55 $\mu$m, $\Delta n_{\text{max}}^2$, for structures of variable $L_{\text{gap}}$, when the electrode $V_1$ is kept fixed at 4 V and $V_2$ ranges from 0 to 20 V. The interdependency of the LC-channels optical properties described in Fig. 7 is further verified; the closer the channels, the smaller

![FIG. 8. (Color online) Effective index of individual modes (blue lines) and supermodes (black lines) for a structure of $L_{\text{gap}} = 600$ nm. The first electrode is kept fixed at $V_1 = 4$ V and voltage of the second electrode, $V_2$ varies from 2 to 12 V.](image)

<table>
<thead>
<tr>
<th>$L_{\text{gap}}$(nm)</th>
<th>$L_c$(µm)</th>
<th>$\Delta n_{\text{eff}}^2$</th>
<th>$\Delta n_{\text{max}}^2$</th>
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</thead>
<tbody>
<tr>
<td>300</td>
<td>22.30</td>
<td>0.06017</td>
<td>0.03710</td>
</tr>
<tr>
<td>400</td>
<td>25.77</td>
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<td>500</td>
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<td>700</td>
<td>39.59</td>
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the contrast in the refractive indices of the two waveguides. Most importantly it is remarked that for small values of $L_{\text{gap}}$, when the coupling length is low, as calculated by CMT, the structure is incapable of providing the required mismatch for the asynchronous operation. As $L_{\text{gap}}$ widens, the coupling length obtains higher values, whereas the interdependency phenomena weaken and above a certain $L_{\text{gap}}$, the required mismatch realizes, that is, $\Delta n_{\text{eff}}^{\text{cr}} < \Delta n_{\text{eff}}^{\text{max}}$. According to Table I and in order to minimize the footprint of the device, the distance between the LC-channels is finally set to $L_{\text{gap}} = 600 \text{ nm}$. This selection yields a coupling length of $L_c = 34.09 \mu\text{m}$, and the transition between the two states of the switch requires a mismatch of modal indices $\Delta n_{\text{eff}} = 0.03937$ at $1.55 \mu\text{m}$, which according to Fig. 8 translates into a selection of the applied voltage values equal to $V_1 = 4 \text{ V}$ and $V_2 = 10.5 \text{ V}$.

V. LC-DLSPP DIRECTIONAL COUPLER OPTICAL SWITCH

Summarizing the conclusions furnished by the coupled-mode theory, when the distance of the LC-channels is equal to $L_{\text{gap}} = 600 \text{ nm}$, and the structure is at the synchronous state ($V_1 = V_2 = 4 \text{ V}$), it is characterized by a coupling length $L_c = 34.09 \mu\text{m}$, whereas when $V_1 = 4 \text{ V}$, $V_2 = 10.5 \text{ V}$, the mismatching condition predicts a minimization of power exchange between the two waveguides at $L_c = 34.09 \mu\text{m}$.

A rigorous analysis of light propagation and power coupling may be provided by simulating the spatiotemporal evolution of the propagating electric and magnetic field with the use of a suitably formulated FDTD method. In the present study, since the materials are non-magnetic, the time-harmonic field magnitudes involved in the calculations are $\mathcal{D}$, $\mathcal{E}$, and $\mathcal{H}$. For the isotropic dielectric materials composing the structure, the spatially dependent vectors $\mathbf{D}$ and $\mathbf{E}$ are associated via their dielectric constant, $\mathbf{D} = \varepsilon_{\text{r}}(\omega)\mathbf{E}$, while for the anisotropic nematic LC via the rank-2 tensor $\varepsilon_\varepsilon$ which in principle has all nine elements nonzero, $\mathbf{D} = \mathbf{e}_\varepsilon \varepsilon_\varepsilon \mathbf{E}$. In order to take into account the highly dispersive properties of the metal stripe, the formulation

$$
\mathbf{D}(\omega) = \varepsilon_0 \left[ 1 + \frac{\omega_p^2}{\omega(i\omega_c - \omega)} \right] \mathbf{E}(\omega) \quad (4)
$$

is adopted. The term in the right part of Eq. (4) accounts for the Drude model describing the metal stripe’s properties at optical frequencies. The terms $\omega_p$ and $\varepsilon_c$ stand for the plasma and collision frequency, respectively. The electrostatic analysis of the coupled structure presented yields the dielectric tensor, which along with the dispersive data are fed into the FDTD algorithm.

Figure 9 plots the calculated optical power flow $P_{z1}$ and $P_{z2}$ that propagates through the two LC-channels along the propagation axis $z$, when the LC-channels are synchronous, the electrodes voltage set to $V_1 = V_2 = 4 \text{ V}$ at the operational wavelength of $1.55 \mu\text{m}$. The LC-channel WG$_1$ is originally excited at the entrance of the coupler ($z = 0$), by the linear combination of the symmetric and antisymmetric mode, with the use of a total-field scattered-field (TF/SF) formulation.

Power flows $P_{z1}$ and $P_{z2}$ are calculated by performing an FFT along the propagation direction in each individual channel. The coupling length computed by FDTD is $L_c = 34.35 \mu\text{m}$ that is very close to the value estimated by the supermode analysis. The decay of the total propagating power, that is the sum of $P_{z1}$ and $P_{z2}$, results mainly from the resistive damping in the metal film. The next step of the design is to set the voltage $V_2$ to the value corresponding to the asynchronous state. According to the results of the CMT, light is expected to couple back to the originally exited LC-channel at a distance $L_c$, when the voltage of the second electrode is $V_2 = 10.5 \text{ V}$. By performing various simulations around the approximate value of $V_2 = 10.5 \text{ V}$, and comparing the lengths of the corresponding maximum power exchange, it has been found that the designated value for the voltage in the asynchronous state is equal to $V_2 = 11.4 \text{ V}$.

Having fixed the values of the various parameters composing the structure, the performance of the proposed device as an optical switch can be evaluated. The schematic layout and the operation principle of the structure are depicted in Fig. 10. Light is launched into the first LC-channel WG$_1$ at $z = 0$ and when the device operates in the synchronous state, power is coupled to the adjacent LC-channel WG$_2$ at a distance equal to $L_c = 34.35 \mu\text{m}$. This case is also referred to as the cross-state of the optical switch. On the other hand, when light is launched into the first LC-channel WG$_1$ at $z = 0$, and the voltage $V_2$ of the electrode rises to the value of $V_2 = 11.4 \text{ V}$, that is when the device operates in the asynchronous state, a small fraction of the power is initially coupled to WG$_2$ but then coupled back to WG$_1$ at a distance equal to $L_c = 34.35 \mu\text{m}$. This case is denominated as the bar-state of the optical switch. It should be mentioned that similar functionality can be provided by other variants derived from the proposed LC-DLSPP structure. For example, the liquid crystal in the fixed-voltage waveguide WG$_1$ could be substituted by a material of electrically invariant and sufficiently high index. If that were the case, there would be a single $V_2$ value for the LC-channel to phase-match the adjacent channel (WG$_1$) and implement the cross-state. However, this would result in an optical switch with the coupling length forced at a fixed value, which cannot be fine-tuned. Contrary to that, the design here presented provides with
more flexibility since both the cross and bar states can be independently tuned by selecting the appropriate common voltage level \( V_1 = V_2 \) for the cross-state and the pair \( (V_1, V_2) \) for the bar-state. This can compensate for small manufacturing impairments and/or thermal variations and lead to better performance at both switch states.

A quantified evaluation of the structure’s performance is provided by calculating the extinction ratio (ER) of the optical switch at the operation wavelength of 1.55 \( \mu \text{m} \), defined as the power propagating through the excited LC-channel, divided by the power coupled in the second LC-channel along the propagation axis that is

\[
\text{ER}(z) = \frac{P_{z1}(z)}{P_{z2}(z)}.
\]  

(5)

According to the results presented in Fig. 11, when the switch is at the cross-state the coupled power is maximized at the output of the device \( z = L_c \) and ER obtains values as low as \(-12.5\) dB. On the other hand, when the switch is at the bar-state and light is coupled back to the originally exited LC-channel, the extinction ratio obtains values of approximately \(-11.9\) dB.

Finally, the insertion losses for bar and cross-states are calculated. Insertion losses are defined as the power measured at the exit of the switch divided by the input power

\[
\text{IL}_{(\text{bar/cross})} = \frac{P_{z1}(z = L_c)}{P_{z1}(z = 0)}
\]  

(6)

and are calculated equal to \(-2.26\) dB and \(-2.32\) dB. The dominant loss mechanism is the ohmic losses of the metallic film. Minor secondary losses may be introduced owing to radiation or the mismatch between the incident mode and the modes supported by the LC-DLSPP waveguides.

VI. CONCLUSIONS

The light guiding properties of a LC-based DLSPP waveguide have been thoroughly analyzed. By loading an Au film with a nematic material that infiltrates a channel waveguide, and by tuning its molecular orientation via electrode pairs, extensive electrical control of the DLSPP plasmonic modal properties is demonstrated. Based on this type of LC-DLSPP waveguides, an implementation of optical switch with externally controllable coupling length and extinction ratio has been investigated. The operating voltage of the proposed component has been found to be relatively low, in the order of 4–12 V, with predicted coupling lengths as low as \( L_c = 34.35 \mu\text{m} \), adequately lower than the propagation length of the LC-DLSPP mode \( L_p = 63 \mu\text{m} \). The extinction ratios for the two states of operation were found equal to 11.9 dB and 12.5 dB for the bar and the cross-state, respectively, with approximately equal insertion losses, in the range of 2.3 dB. Such electrically controlled dynamic plasmonic devices may provide a promising alternative in terms of controlling and routing of optical signals in integrated plasmonics-based optical chips.

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