Tunability of plasmonic devices

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Rome (Italy)

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Outline

- Passive Plasmonic waveguides
- Tunability by thermo-optic effect
- Tunability by absorption
- Tunability by electro-optic optic in $LiNbO_3$
- Tunability by electro-optics optic in Liquid Crystals
- Liquid Crystals optical switches
- Liquid Crystals directional coupler switches

In all cases, we need to change, by some means, either the real or imaginary part of the index of either the metal or some of the surrounding dielectrics

Metal Stripe Plasmonic Waveguides

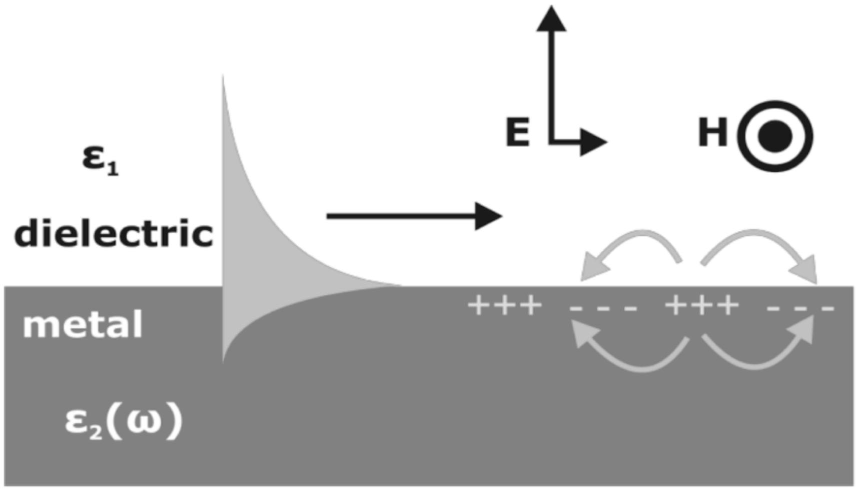
- **Surface Plasmon Polaritons (SPPs):** EM surface waves coherently coupled to free electron oscillations on a metal/dielectric interface.
- **Metal at NIR →** **Drude model**: Re{ε_2}<0 ▪ SPP waves propagate along the interface. ▪ Fields decay exponentially away from it.
- **Trade-off→losses vs. lateral confinement** × Suffer ohmic propagation losses (metal). ✓ Confinement surpasses Diffraction Limit.

Plasmonics for Optical Communications

Integrated photonic components with...

✓ **Lateral dimensions →** far-below diffraction limit (λ/2)

✓ **Control** & **Information** signals collocated @ metal/dielectric interface ...leading to **Nanoscale Opto-Electronic Devices**.



SPP at single metal/dielectric interface: An elementary plasmonic waveguide

Long-Range Surface Plasmon Polariton (LR-SPP) Waveguides

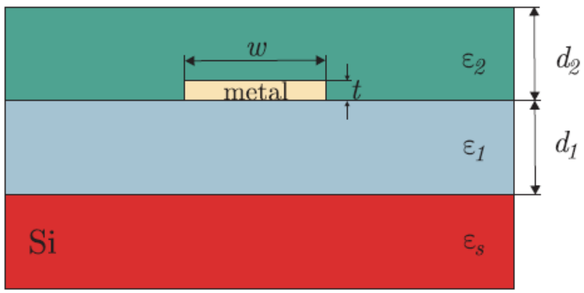
Long-Range Surface Plasmon Polariton Metal Stripe Waveguides:

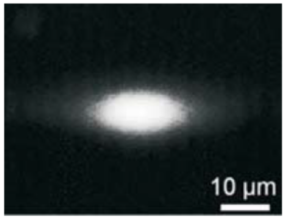
Long-Range: attenuation 100-1000 times lower than single metal/dielectric polariton wave -> propagation distance few cm

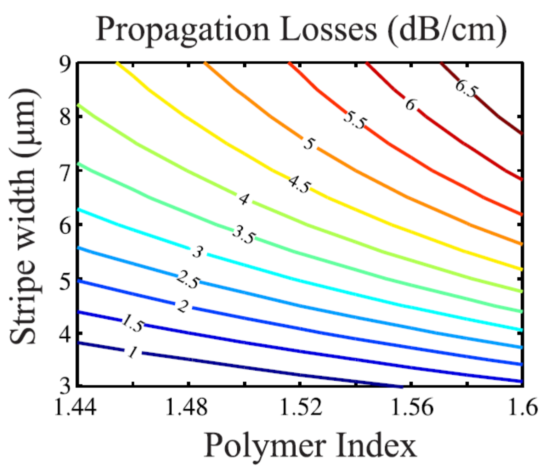
Surface Plasmon Polariton: light is coupled to oscillations of free electron plasma and propagates as a surface wave on the metal/dielectric interface

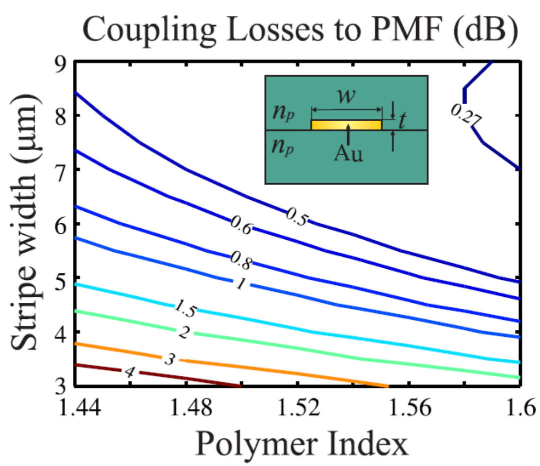
Metal stripe: a thin metal stripe, gold or silver, is employed with typical dimensions in the μm x nm range (width x thickness)

Modal confinement comparable to single-mode fibers









Long-Range Metal Stripe Plasmonic Waveguides

Long-Range Surface Plasmon Polariton Metal Stripe Waveguides:

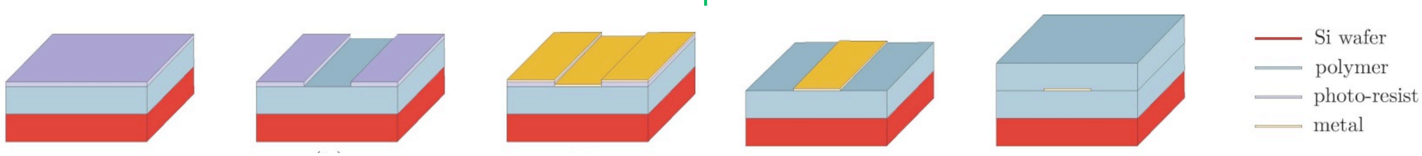
Fabrication: polymer spin-coating and a single metal formation cycle (lithography, metal deposition, liftoff). Features can be defined down to the critical dimensions of litho process

Low losses: lowest losses reported down to 1 dB/cm

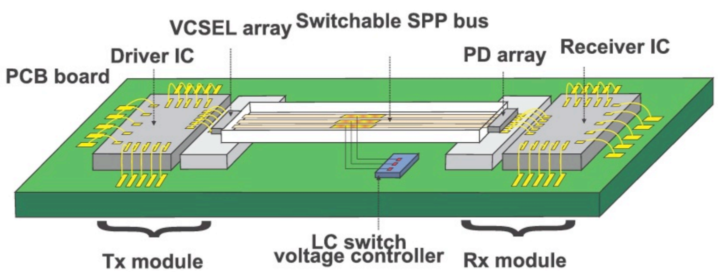
Single-mode: the stripe supports a fundamental TM-polarized mode, no interference with cross-polarized light

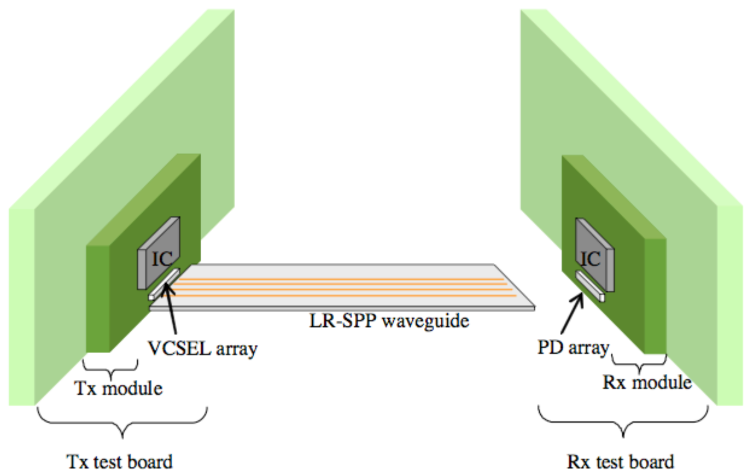
Electrical access: the underlying metal network allows for the transmission of electrical control signals -> thermo-/electro-optic components

LR-SPP fabrication process chain



Chip-to-chip interconnects





Dielectric Loaded Plasmonic Waveguides

PHYSICAL REVIEW B **75**, 245405 (2007)

Theoretical analysis of dielectric-loaded surface plasmon-polariton waveguides

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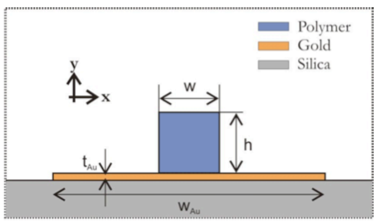
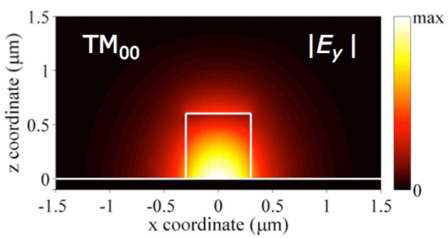
(Received 15 December 2006; revised manuscript received 16 March 2007; published 6 June 2007)

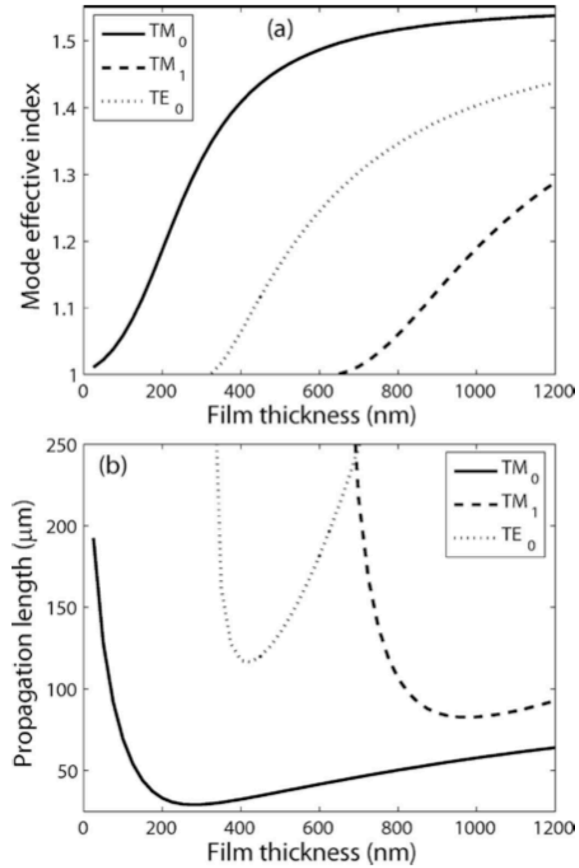
Waveguiding of surface plasmon-polaritons (SPPs) by a dielectric ridge placed on a metal surface is analyzed using the effective-index method (EIM) and the finite element method (FEM). Main characteristics of these dielectric-loaded SPP waveguide (DLSPPW) structures, i.e., the mode effective index, confinement, and propagation length, are calculated at the telecom wavelength $\lambda = 1.55$ μm for different widths and thicknesses of a polymer ridge (with the refractive index of 1.535) placed on a gold film surface. The condition for single-mode guiding is investigated using the EIM, and it is found that single-mode DLSPPW guiding can be realized for ridge thicknesses smaller than ~630 nm and widths below ~655 nm (when decreasing the ridge thickness, the ridge width suitable for single-mode guiding increases). It is also established that, in contrast to the usual trade-off, the DLSPPW mode lateral confinement can be improved simultaneously with the increase in the mode propagation length by choosing the appropriate ridge thickness. The accuracy of the EIM is evaluated by comparing the computed mode characteristics with those obtained with the FEM and found rather good for the modes being far from cutoff.

DOI: 10.1103/PhysRevB.75.245405 PACS number(s): 73.20.Mf, 71.36.+c, 78.20.Bh, 42.79.Gn





$w \times h = 500 \times 600$ nm^2 // $t_{Au} = 100$ nm
$n_{pol} \sim 1.5$ // $\varepsilon_{r,Au} = -132 - j*12.65$ @ $\lambda = 1.55$ μm



Channel Plasmon Polariton (CPP) Waveguides

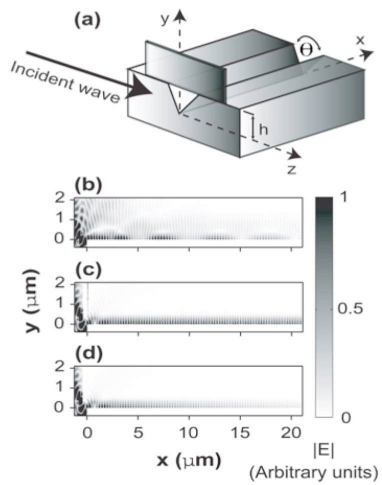
APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 26 27 DECEMBER 2004

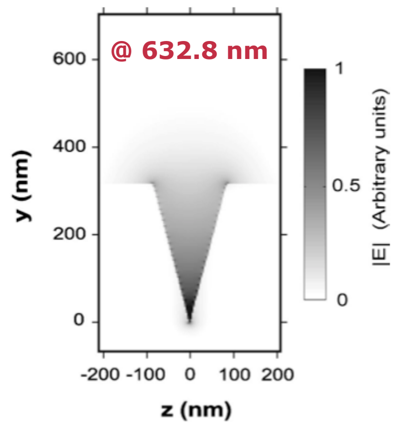
Single-mode subwavelength waveguide with channel plasmon-polaritons in triangular grooves on a metal surface

D. K. Gramotnev and D. F. P. Pile[a)]
Applied Optics Program, School of Physical and Chemical Sciences, Queensland University of Technology, GPO Box 2434, Brisbane, QLD 4001, Australia

(Received 9 August 2004; accepted 19 October 2004)

We demonstrate that single-mode operation of a subwavelength plasmonic waveguide in the form of a V-groove on a metal surface can be achieved by adjusting the depth of the groove. Strongly localized channel plasmon-polaritons (CPPs) are shown to propagate in such waveguides. If the groove depth is close to the penetration depth of the fundamental CPP mode, then all higher modes are not supported by the structure, leaving only the fundamental mode propagating in the groove. In this case, propagation distances of fundamental mode ~10 μm can easily be achieved together with strong subwavelength localization. © *2004 American Institute of Physics*.
[DOI: 10.1063/1.1839283]





Very lossy but really sub-wavelength

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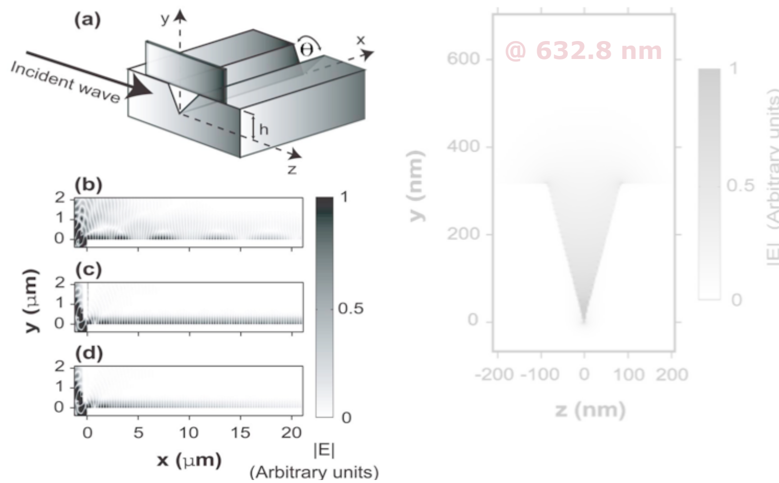


Very lossy but really sub-wavelength

PRL **95,** 046802 (2005) PHYSICAL REVIEW LETTERS week ending 22 JULY 2005

Channel Plasmon-Polariton Guiding by Subwavelength Metal Grooves

Sergey I. Bozhevolnyi,[1,*] Valentyn S. Volkov,[1] Eloïse Devaux,[2] and Thomas W. Ebbesen[2]
[1]*Department of Physics and Nanotechnology, Aalborg University, Pontoppidanstræde 103, DK-9220 Aalborg Øst, Denmark*
[2]*Laboratoire des Nanostructures, ISIS, Université Louis Pasteur, 8 allée Monge, BP 70028, 67083 Strasbourg, France*
(Received 4 February 2005; published 22 July 2005)

We report on realization of channel plasmon-polariton (CPP) propagation along a subwavelength metal groove. Using imaging with a near-field microscope and end-fire coupling with a tapered fiber connected to a tunable laser at telecommunication wavelengths (1425–1620 nm), we demonstrate low-loss (propagation length ~100 μm) and well-confined (mode width ≅ 1.1 μm) CPP guiding along a triangular 0.6 μm-wide and 1 μm-deep groove in gold. We develop a simple model based on the effective-index method that accounts for the main features of CPP guiding and provides a clear physical picture of this phenomenon.

DOI: 10.1103/PhysRevLett.95.046802 PACS numbers: 73.20.Mf, 07.79.Fc, 71.36.+c

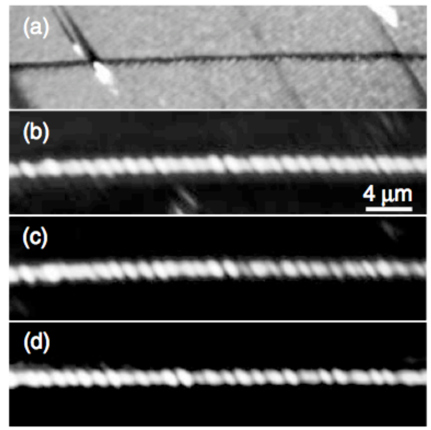


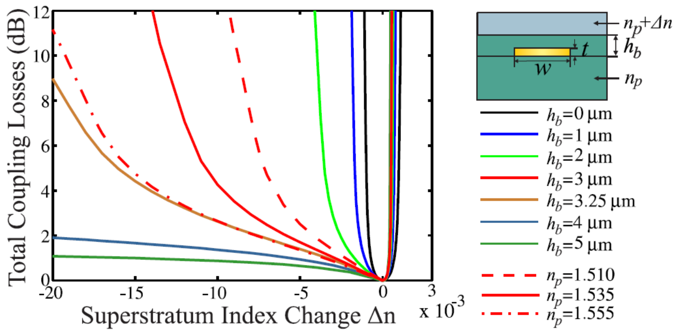
FIG. 4. Grayscale (a) topographical and near-field optical images (36 × 9 μm^2) taken with groove N2 at $\lambda \cong$ (b) 1.44, (c) 1.5, and (d) 1.57 μm. The CPP propagation is from left to right.

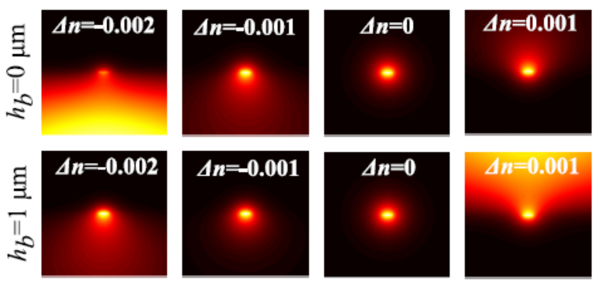
Now let us try to provide some tuning to the waveguides....

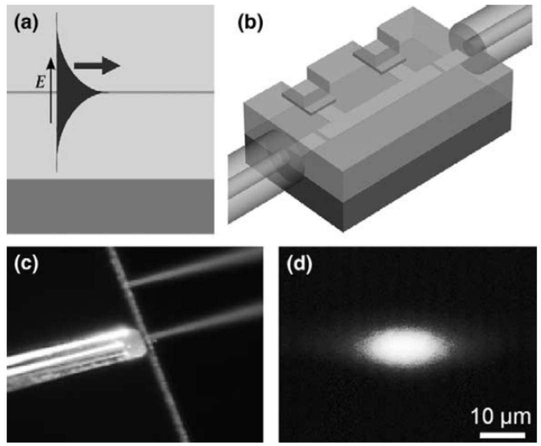
Tunability by thermo-optic effect LRSPP Waveguides & Components

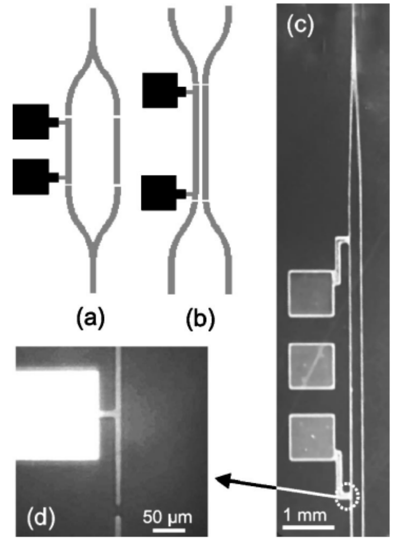
Heating a ***symmetrical*** structure tunes the modal index and phase difference: MZIs, DCSs...

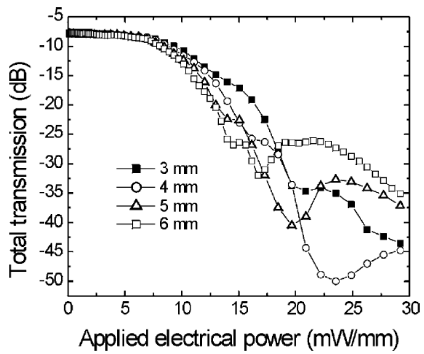
Heating an asymmetrical structure leads to excessive light leakage: VOAs...



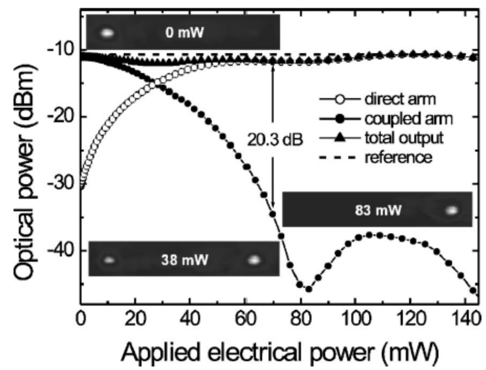








Nikolajsen *et al.*,
Opt. Comm. **244**, 455 (2005)



Nikolajsen *et al.*,
APL **85**, 5833 (2004)

Tunability by absorption in the "metal" stripe

- Plasmon is guided by a highly conductive metal-oxide ($N \approx 10^{18} cm^3$)
- Ag electrodes far apart and play little role
- Voltage changes the charge density in the highly conductive semiconductor, hence $n=n_r+jn_j$, hence absorption, hence power transmitted at the output

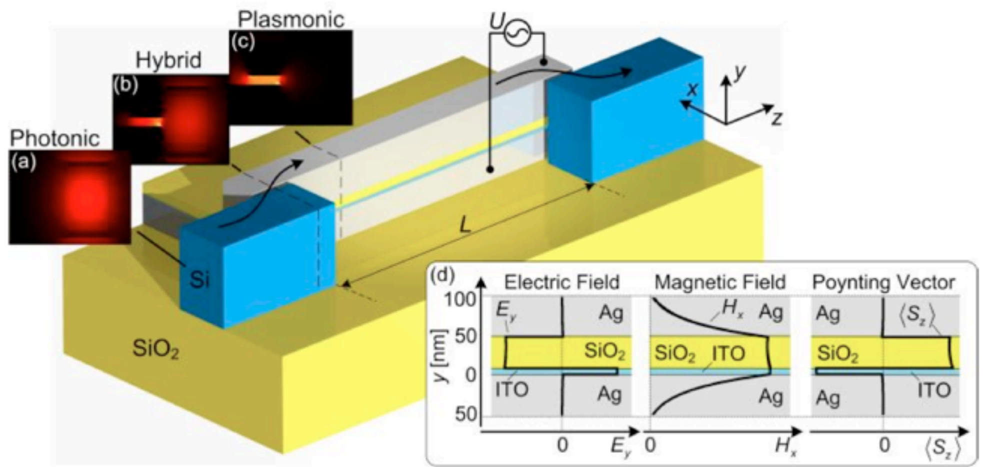


Fig. 1. The structure of a surface plasmon polariton absorption modulator (SPPAM). Light is coupled from a silicon nanowire into an active plasmonic section by means of a directional coupler. The active section consists of a stack of silver (Ag), indium tin oxide (ITO), and SiO_2 layers. The absorption coefficient of the SPP is modulated by applying a voltage between the two silver electrodes. The insets show how a photonic mode (a) in a silicon strip waveguide excites a SPP (c) via a hybrid mode (b) in directional coupler. The insets in (d) show the electric field E_y and the magnetic field H_x as well as the time-averaged Poynting vector distributions $\langle S_z \rangle = \mathrm{Re}\{E \times H\}/2$ in the active plasmonic part. The plot of the Poynting vector shows the power confinement of the SPP in the ITO layer. The length L describes the size of the modulator along the light propagation direction.

Optics Express 19, 8855 (2011)

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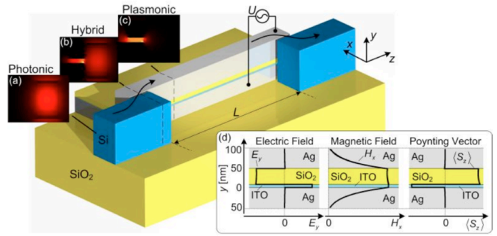

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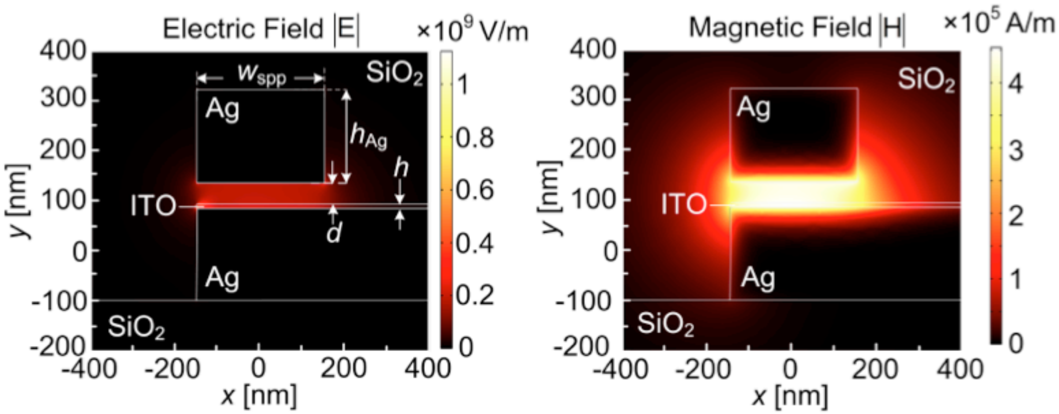

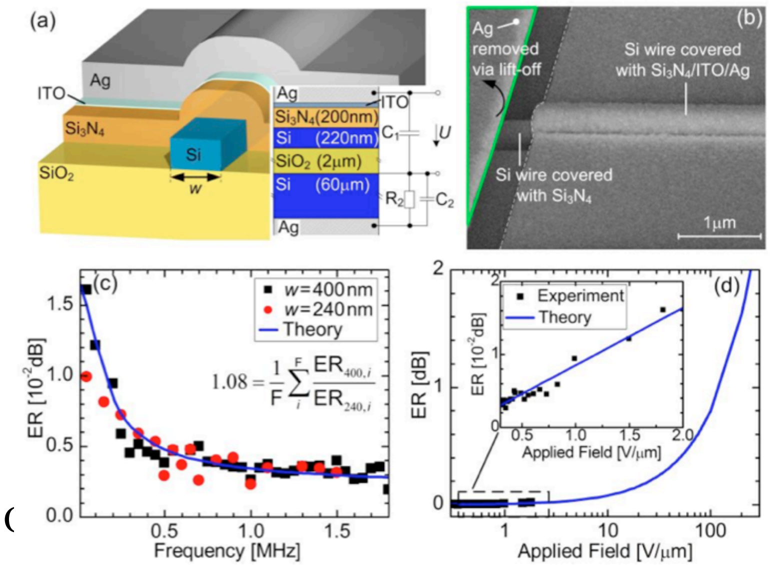

Tunability of LR-SPP by electro-optic optic in $LiNbO_3$

APPLIED PHYSICS LETTERS **90**, 061108 (2007)

Wafer-bonded surface plasmon waveguides

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Greg Mattiussi[b)]
Epocal Corporation, Ottawa, Ontario K1G 6C6, Canada

Nancy Lahoud
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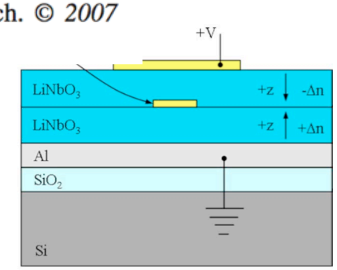
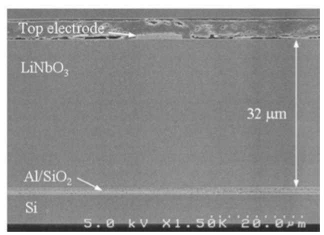
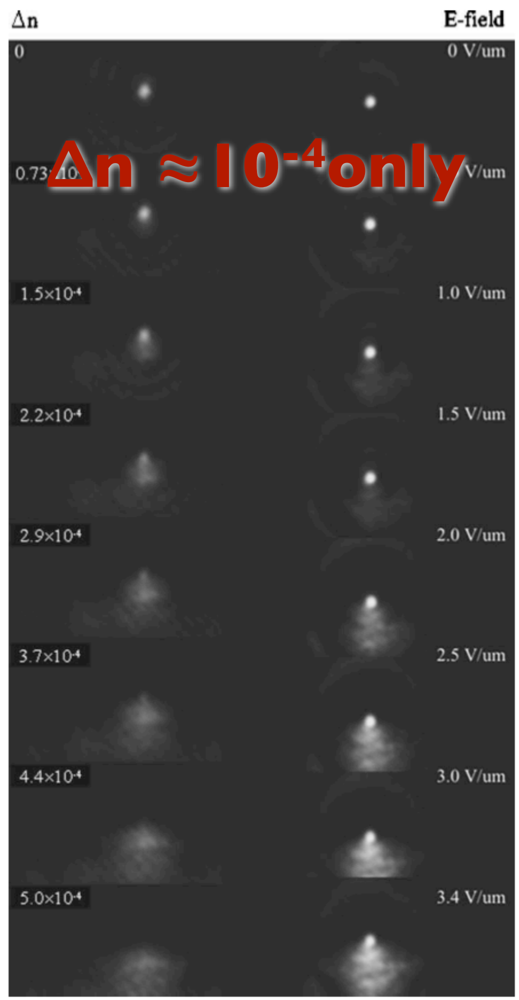
Defence Research and Development, Sheppard Avenue West, P.O. Box 2000, Ontario M3M 3B9, Canada

(Received 12 December 2006; accepted 9 January 2007; published online 7 February 2007)

Direct wafer bonding and thinning were explored as an approach for constructing long-range surface plasmon waveguides. The structures consist of a thin metal stripe deposited into a shallow trench etched into one of the claddings, to which another cladding of the same material is directly bonded. The approach was developed first using Pyrex wafers in order to assess feasibility and then using lithium niobate wafers. Optical and electro-optical measurements validate the approach. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2468660]

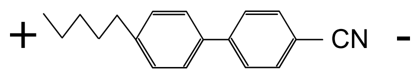






4 mm long

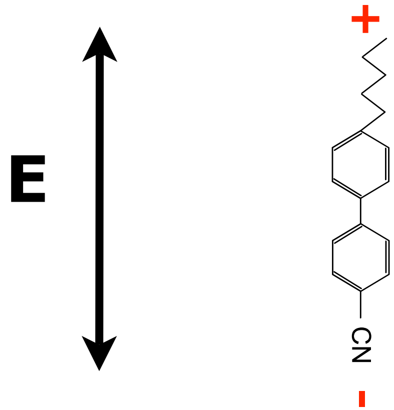
Tunability by electro-effect optic in Liquid Crystals



cyano-biphenyl 5CB
2 nm long, 0.5 nm large

From the rod-like form of molecules → Anisotropy (electric and optical)

Tunability by electro-effect optic in Liquid Crystals



cyano-biphenyl 5CB
2 nm long, 0.5 nm large

From the rod-like form of molecules → Anisotropy (electric and optical) → Re-orientation (electric and optical)

Lab on a Chip

Dynamic Article Links

Cite this: DOI: 10.1039/c2lc40514h

www.rsc.org/loc

CRITICAL REVIEW

Guided-wave liquid-crystal photonics†

D. C. Zografopoulos,*[a] R. Asquini,[b] E. E. Kriezis,[c] A. d'Alessandro[ab] and R. Beccherelli[a]

Received 4th May 2012, Accepted 13th June 2012
DOI: 10.1039/c2lc40514h

In this paper we review the state of the art in the field of liquid-crystal tunable guided-wave photonic devices, a unique type of fill-once, molecular-level actuated, optofluidic systems. These have recently attracted significant research interest as potential candidates for low-cost, highly functional photonic elements. We cover a full range of structures, which span from micromachined liquid-crystal on silicon devices to periodic structures and liquid-crystal infiltrated photonic crystal fibers, with an focus on key-applications for photonics. Various approaches on the control of the LC molecular orientation are assessed, including electro-, thermo- and all-optical switching. Special attention is paid to practical issues regarding liquid-crystal infiltration, molecular alignment and actuation, low-power operation, as well as their integrability in chip-scale or fiber-based devices.

Tunability by electro-effect optic in Liquid Crystals

- Free space Liquid Crystal On Silicon (LCOS) μdisplays and Spatial Light Modulator
- Free space Fabry-Perot Tunable Filter and Tunable Lasers
- LC as a tunable cladding for a SOI slab and rib waveguides
- LC waveguide embedded in micromachined silicon as an integrated optics polarizer
- LC waveguide embedded in micromachined silicon as an electrically controlled optical waveguide
- LC waveguide embedded in micromachined silicon as an optically controlled optical waveguide
- LC as tunable index medium in photonic crystals
- LC as tunable medium in composite holographic gratings
- LC as tunable cladding for Ring Resonators

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- LC as tunable index medium in photonic crystals
- LC as tunable medium in composite holographic gratings
- LC as tunable cladding for Ring Resonators
- High Q whispering gallery mode spherical resonators

Power consumption in μWcm^{-2}, typical devices area 10^{-7} - 10^{-3} cm^{2}

Tunability by electro-effect optic in Liquid Crystals

- ☐ Free space Liquid Crystal On Silicon (LCOS) μdisplays and Spatial Light Modulator
- ☐ Free space Fabry-Perot Tunable Filter
- ☐ LC as a tunable cladding for a SOI slab and rib waveguides
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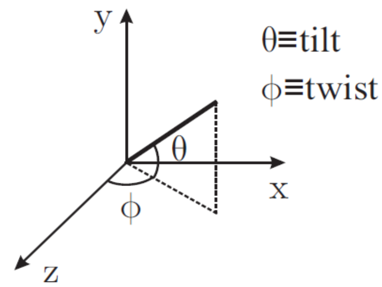
- ☐ LC as tunable cladding for Ring Resonators
- ☑ High Q whispering gallery mode spherical resonators

- **What about tuning plasmonic waveguides with liquid crystals?**

Liquid-Crystal Modeling to determine the dielectric tensor profile

$$\tilde{\varepsilon}_r = \varepsilon_0 \begin{bmatrix} \varepsilon_\perp + \Delta\varepsilon \cos^2\theta \sin^2\phi & \Delta\varepsilon \cos\theta \sin\phi \sin\theta & \Delta\varepsilon \cos^2\theta \sin\phi \cos\phi \\ \Delta\varepsilon \cos\theta \sin\phi \sin\theta & \varepsilon_\perp + \Delta\varepsilon \sin^2\theta & \Delta\varepsilon \sin\theta \cos\theta \cos\phi \\ \Delta\varepsilon \cos^2\theta \sin\phi \cos\phi & \Delta\varepsilon \sin\theta \cos\theta \cos\phi & \varepsilon_\perp + \Delta\varepsilon \cos^2\theta \cos^2\phi \end{bmatrix}$$



Total energy in the LC bulk: elastic + electrostatic

$$F_{\text{tot}} = \iiint_V F_d \, dV = \iiint_V \left(F_{\text{elast}} + F_{\text{elec}}\right) \, dV$$

Nematic director: describes local orientation of LC molecules

$$F_{\text{elast}} = F_{\text{splay}} + F_{\text{twist}} + F_{\text{bend}} = \frac{K_{11}}{2}(\nabla\cdot\mathbf{n})^2 + \frac{K_{22}}{2}(\mathbf{n}\cdot\nabla\times\mathbf{n})^2 + \frac{K_{33}}{2}|\mathbf{n}\times\nabla\times\mathbf{n}|^2$$

Elastic deformations

$$F_{\text{elec}} = -\frac{1}{2}\tilde{\varepsilon}\mathbf{E}\cdot\mathbf{E} = -\frac{\varepsilon_0}{2}\left(\varepsilon_\perp|\mathbf{E}|^2 + \Delta\varepsilon\,(\mathbf{E}\cdot\mathbf{n})^2\right)$$

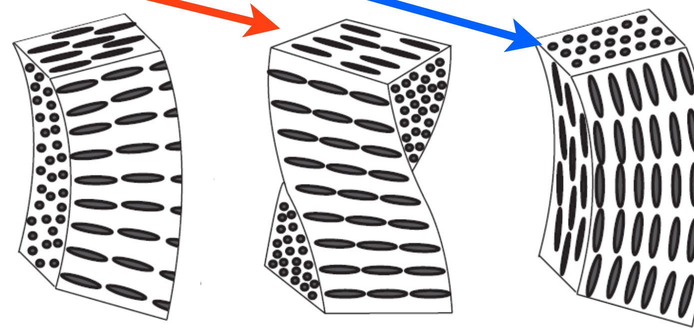
Minimization: two Euler-Lagrange PD equations…

$$\frac{\partial F_d}{\partial\theta} - \frac{\partial}{\partial x}\left(\frac{\partial F_d}{\partial\frac{\partial\theta}{\partial x}}\right) - \frac{\partial}{\partial y}\left(\frac{\partial F_d}{\partial\frac{\partial\theta}{\partial y}}\right) = 0$$

$$\frac{\partial F_d}{\partial\phi} - \frac{\partial}{\partial x}\left(\frac{\partial F_d}{\partial\frac{\partial\phi}{\partial x}}\right) - \frac{\partial}{\partial y}\left(\frac{\partial F_d}{\partial\frac{\partial\phi}{\partial y}}\right) = 0$$

$$\nabla\cdot\mathbf{D} = 0$$

[for z-invariant structures: optical waveguides]



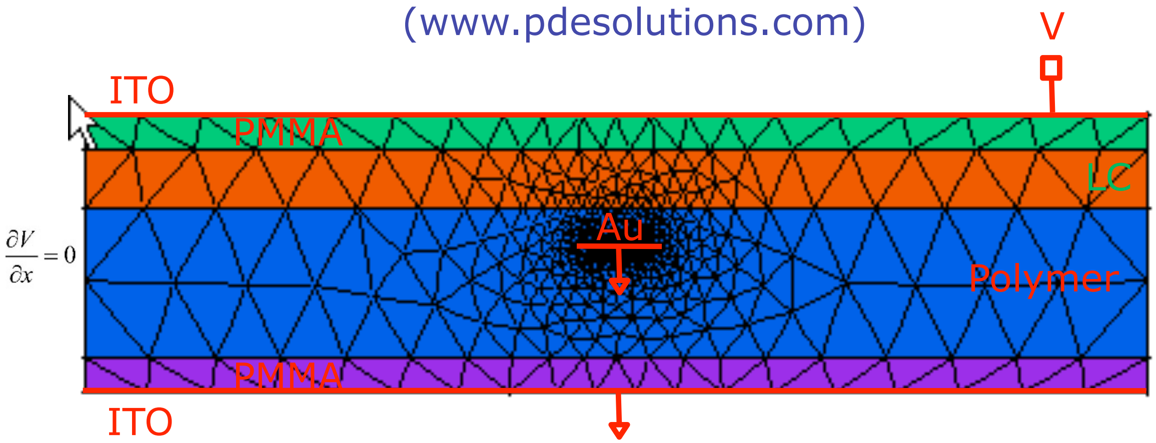
Splay Twist Bend

Solving for tilt (θ), twist (φ), and electrostatic potential (V)

LC-LRSPP: Liquid-Crystal Modeling

The set of Euler-Lagrange PDEs is solved on the nodes of a finite-element mesh via a commercial solver

(www.pdesolutions.com)

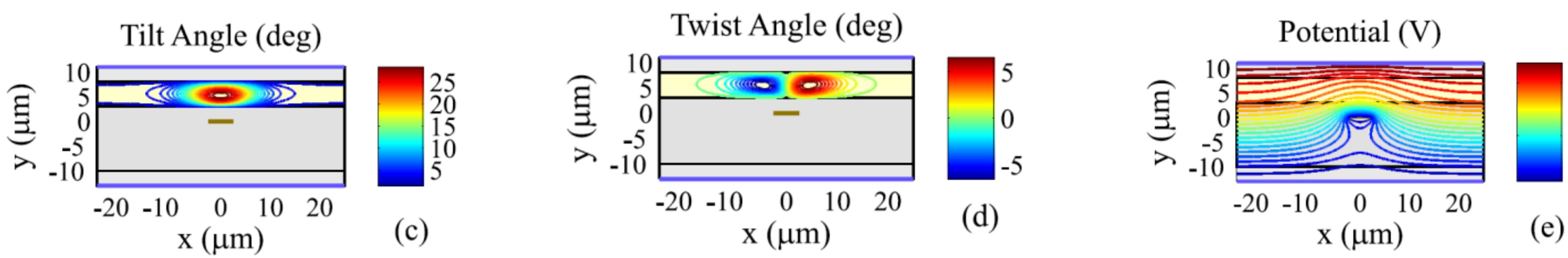


Boundary Conditions:

θ,φ: hard anchoring

V: Neumann (away from region of interest)

Alternatively, you can minimise F_{tot} by using a weak formulation (e.g. in COMSOL www.comsol.com)

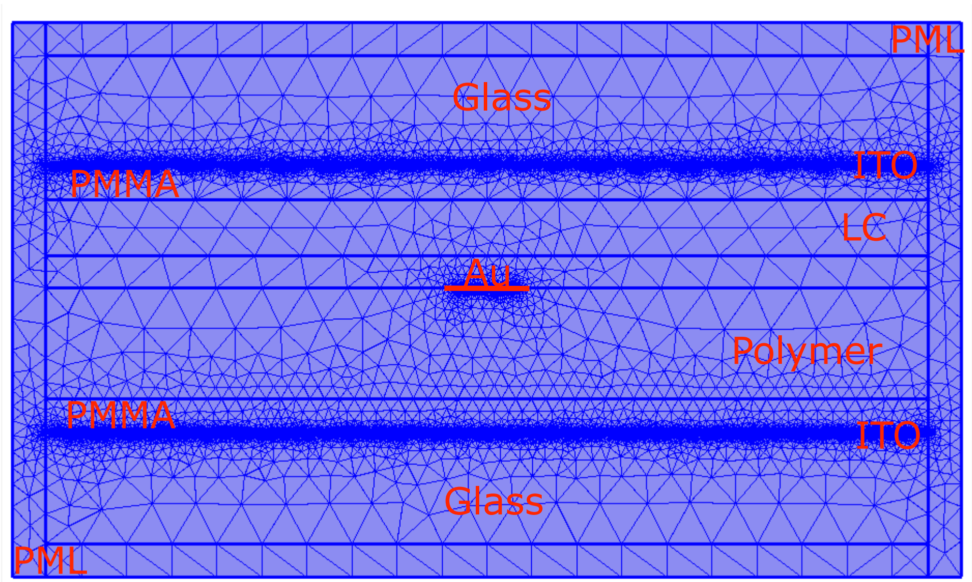


LC-LRSPP: Optical Studies

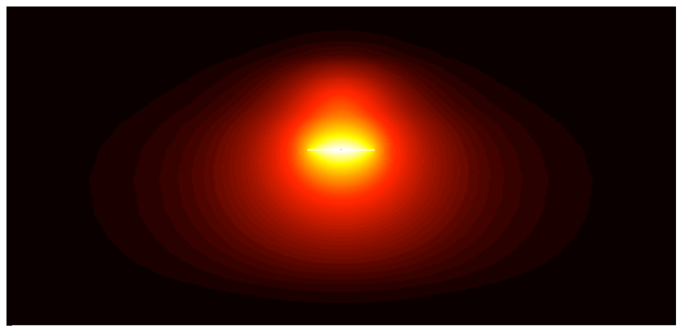
Optical studies conducted via a fully-anisotropic, vectorial finite-element eigensolver (www.comsol.com)

$$\tilde{\varepsilon}_r = \varepsilon_0 \begin{bmatrix} \varepsilon_\perp + \Delta\varepsilon \cos^2\theta \sin^2\phi & \Delta\varepsilon \cos\theta \sin\phi \sin\theta & \Delta\varepsilon \cos^2\theta \sin\phi \cos\phi \\ \Delta\varepsilon \cos\theta \sin\phi \sin\theta & \varepsilon_\perp + \Delta\varepsilon \sin^2\theta & \Delta\varepsilon \sin\theta \cos\theta \cos\phi \\ \Delta\varepsilon \cos^2\theta \sin\phi \cos\phi & \Delta\varepsilon \sin\theta \cos\theta \cos\phi & \varepsilon_\perp + \Delta\varepsilon \cos^2\theta \cos^2\phi \end{bmatrix}$$

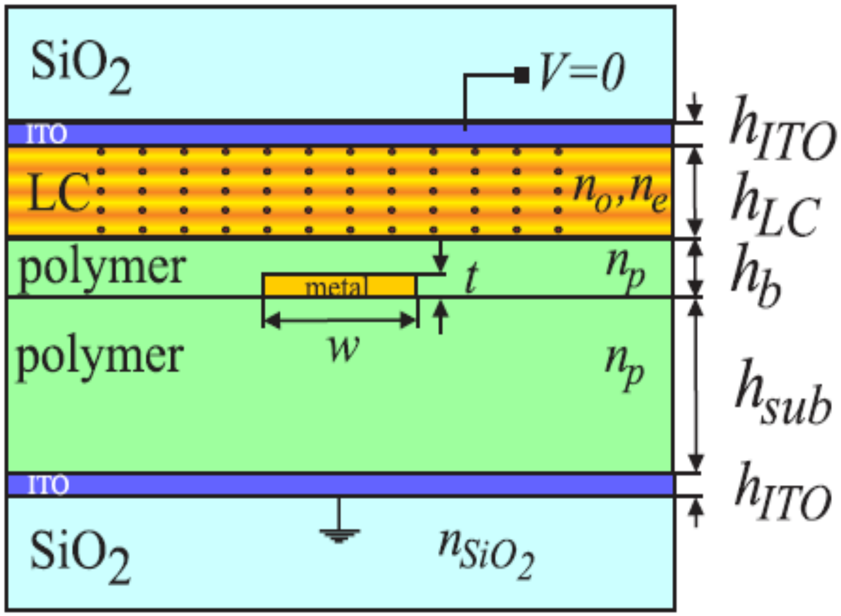
key-element for TM-polarized LC-LRSPP modes

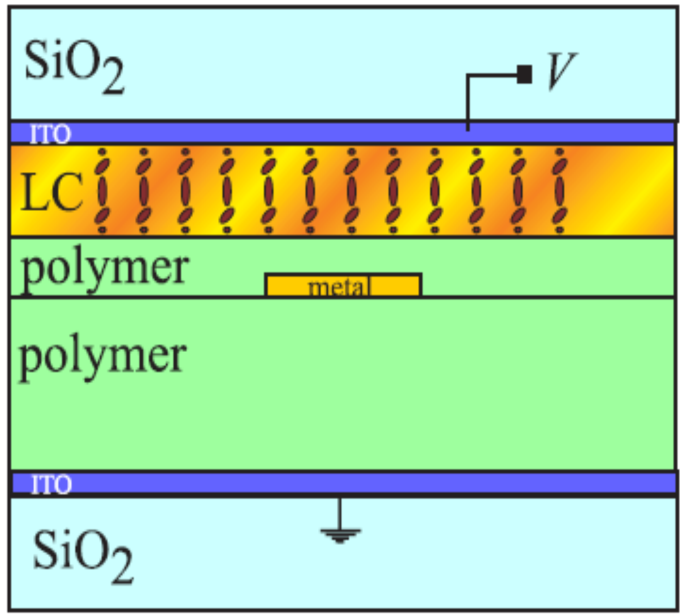


Solving for modal effective indices, propagation losses, modal effective area, optical profiles etc…



LC-LRSPP Variable Optical Attenuator (LR0)





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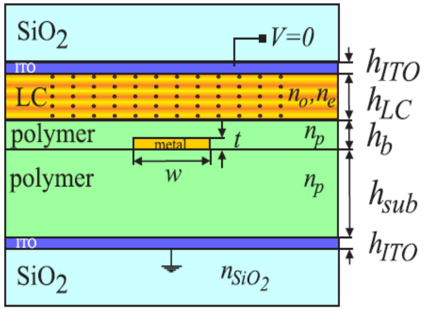

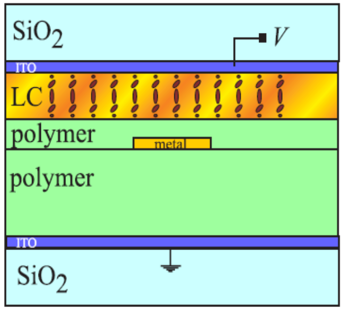

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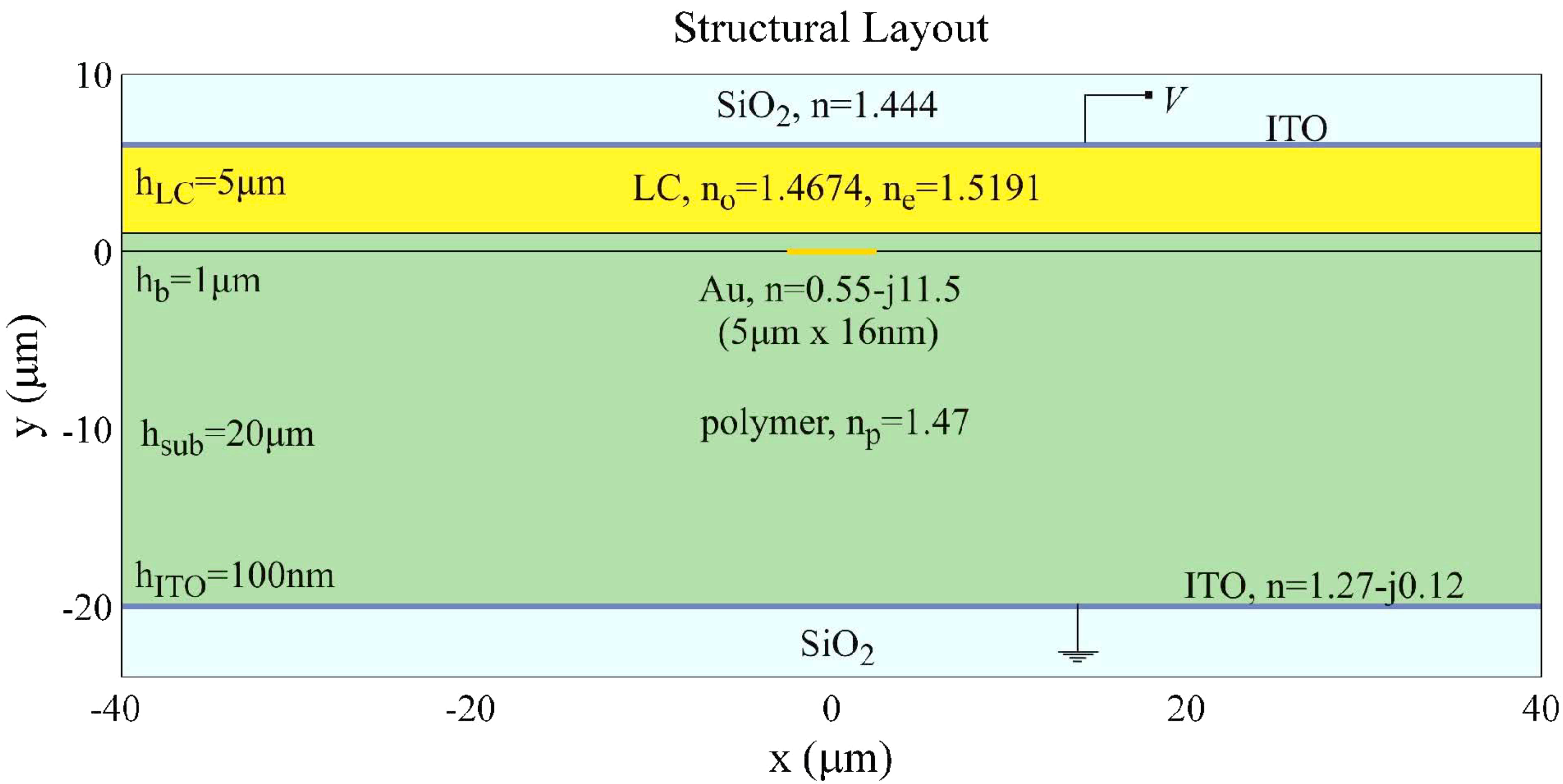
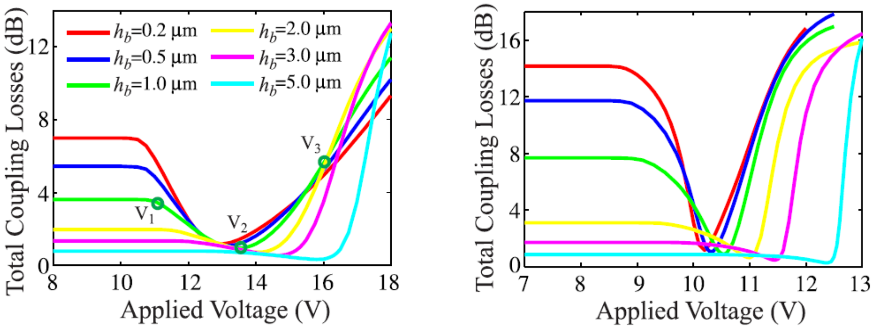


Light is initially confined in the bottom cladding

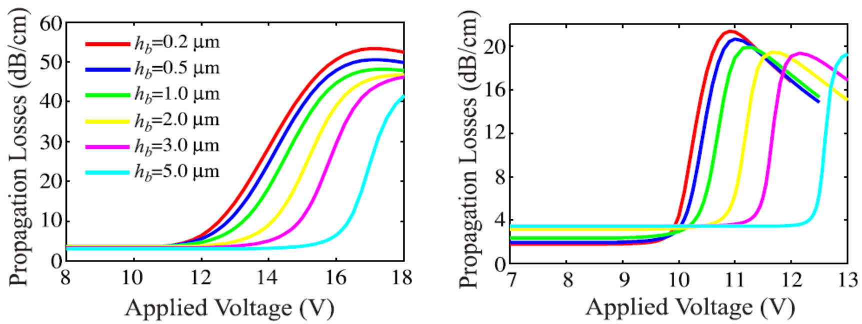
Above an LC switching voltage threshold light escapes into the high-tilt LC-zone

Further increase of voltage increases the LC-slab waveguide modal area and propagation losses

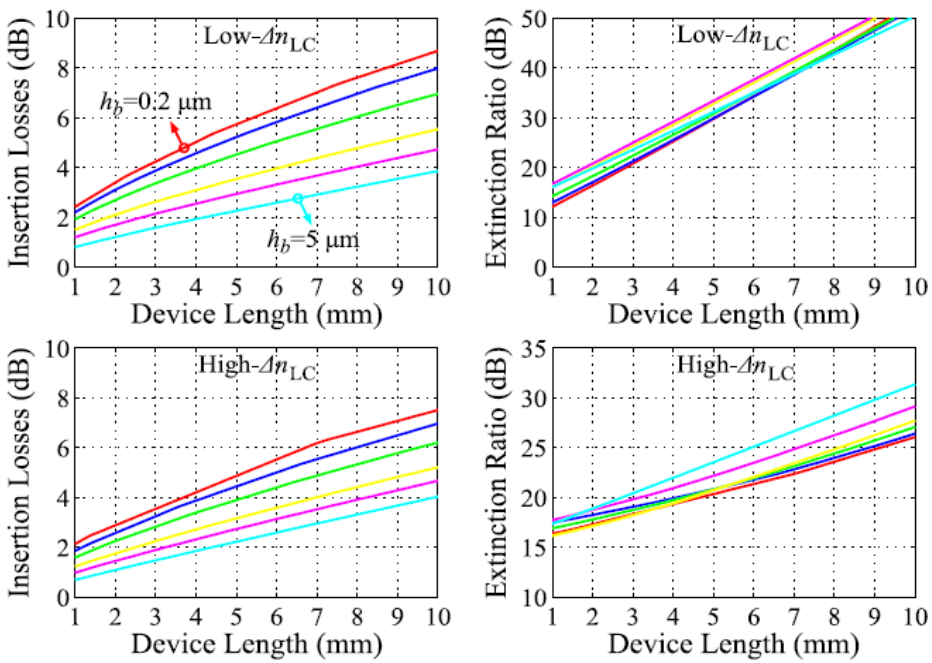
LC-LRSPP Variable Optical Attenuator (LR0)



n_e=1.5024 n_o=1.687 Δn=0.1687



n_e=1.4678 n_o=1.519



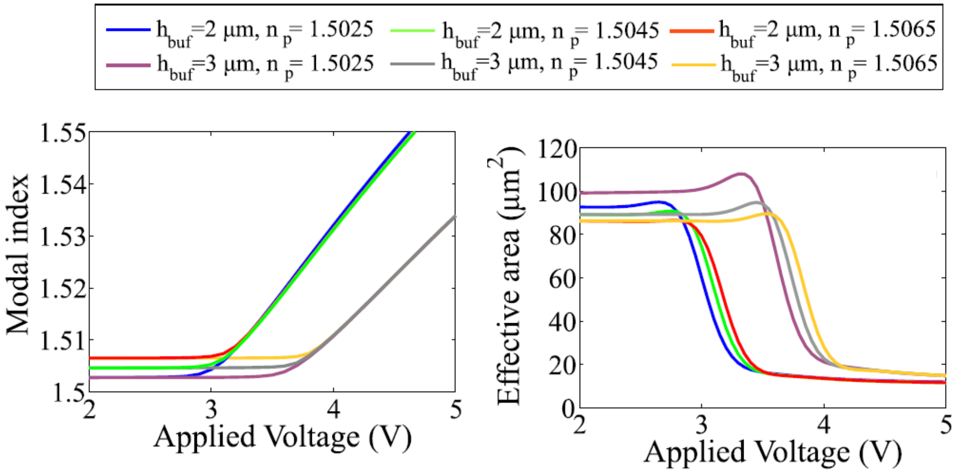
Total losses = coupling losses (owing to modal mismatch, calculated for a PM-SMF fiber) + propagation losses (ohmic resistance of ITO layers)

$$T = -10\log_{10}\left(\frac{\left|\iint_{S_\infty} E_{y1}E_{y2}^{*}dS\right|^2}{\iint_{S_\infty}\left|E_{y1}\right|^2 dS \iint_{S_\infty}\left|E_{y2}\right|^2 dS}\right)$$

- *Variable optical attenuation*
- *ON-OFF switching*

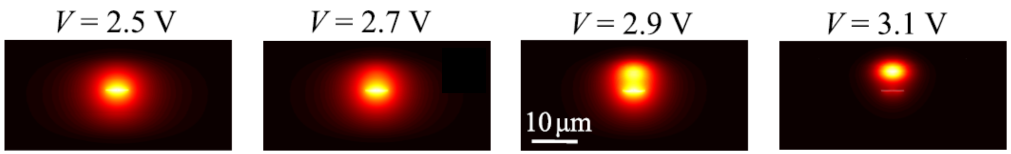
LC-LRSPP plasmon-LC waveguide conversion (LR0)

Optical studies



Above the LC switching threshold light escapes into the high-tilt LC-zone. Further increase of voltage raises the LC-waveguide index and reduces modal area, enhancing field confinement.

The fundamental LRSPP mode is progressively converted into a LC-dielectric one, as higher voltage values lead to increased tilt above the metal stripe



- *Hybrid plasmonic-LC coupling*
- *Phase control elements*
- *Building blocks for more complex components: modulators, interferometers, directional couplers/switches*

LC-LRSPP plasmon-LC waveguide (LR2)

Photonics and Nanostructures (2012) at press

Liquid-Crystal Tunable Waveguides for Integrated Plasmonic Components

D. C. Zografopoulos[a,*], R. Beccherelli[a], A. C. Tasolamprou[b], and E. E. Kriezis[b]

[a] *Consiglio Nazionale delle Ricerche, Istituto per la Microelettronica e Microsistemi (CNR-IMM), Roma 00133, Italy*
[b] *Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki GR-54124, Greece*

Abstract

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Keywords: Plasmonics, integrated optics, liquid-crystal devices.
PACS: 42.82.Et, 78.68.+m, 42.70.Df

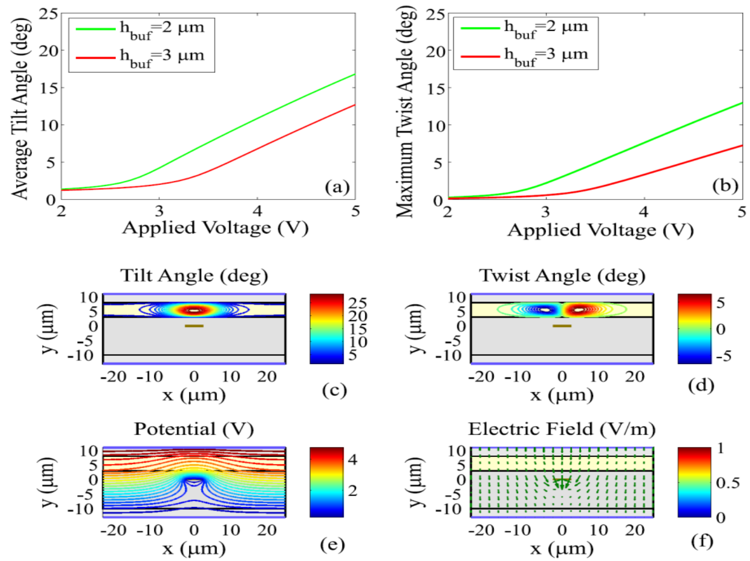
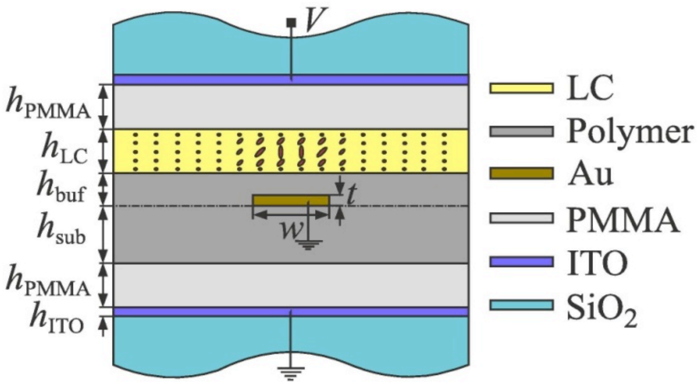


Figure 5: (a) Average tilt and (b) maximum twist angle calculated in the applied voltage range $2 < V < 5$ V for two values of the buffer layer thickness of the waveguide LR2. (c-f) Tilt, twist, electrostatic potential, and electric field profiles at $V = 5$ V for $h_{buf} = 3$ μm. A high-tilt zone is formed above the grounded metal stripe.



- Here, the metal stripe is grounded
- Here, a PMMA Polymer layer isolate the optical field from the conductive ITOs, for lower losses
- The application of voltage creates a high-tilt zone above the stripe and consequently a high-index zone sensed by TM-polarization

LC dielectric loaded SPP optical switches (DL0)

JOURNAL OF APPLIED PHYSICS **110**, 093102 (2011)

Liquid crystal-based dielectric loaded surface plasmon polariton optical switches

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[2]*Displays and Photonics Applications Group, Electronics Technology Department, Carlos III University of Madrid, Leganés E-28911, Madrid, Spain*
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(Received 20 July 2011; accepted 29 September 2011; published online 2 November 2011)

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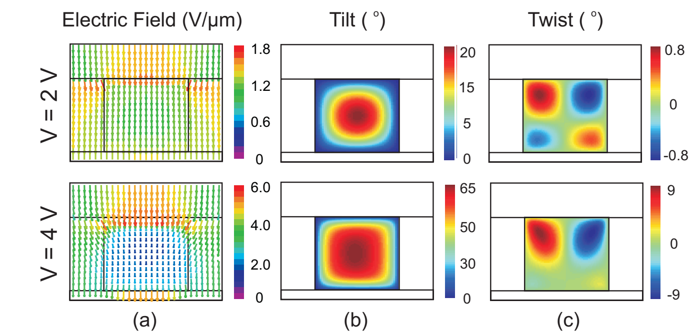

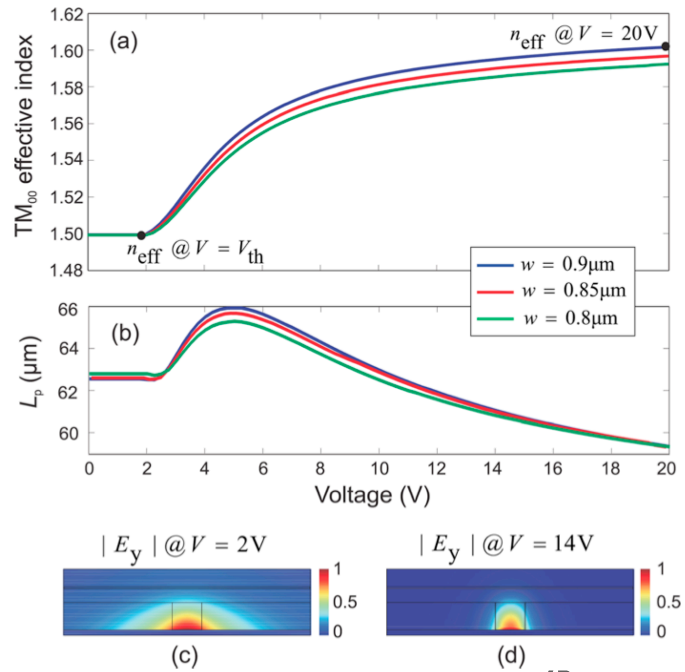

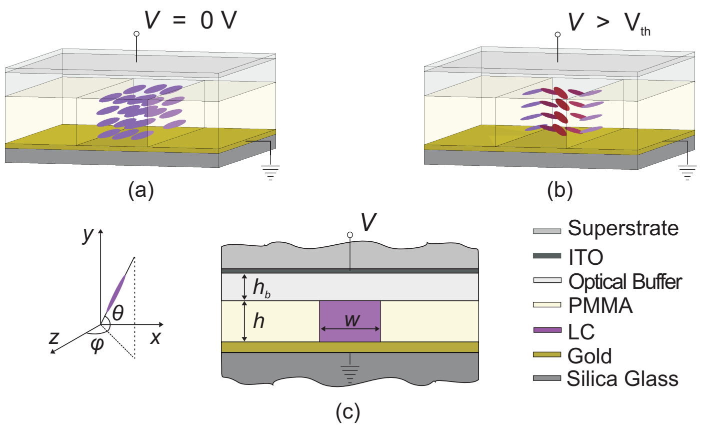

Liquid crystal-based dielectric loaded SPP optical switches (DL1)

Photonics and Nanostructures (2012) at press

Liquid-Crystal Tunable Waveguides for Integrated Plasmonic Components

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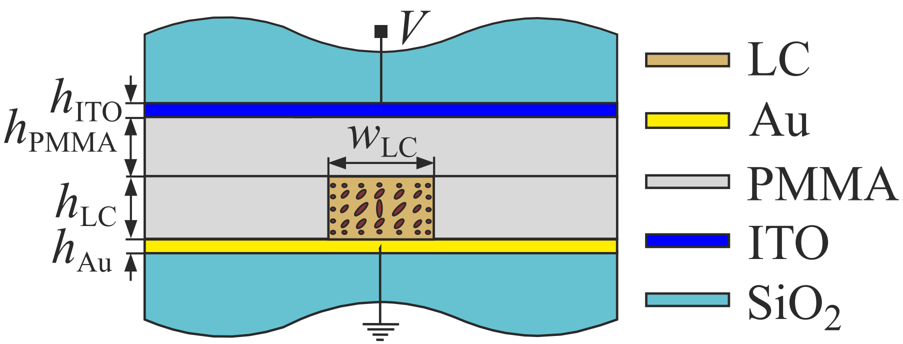
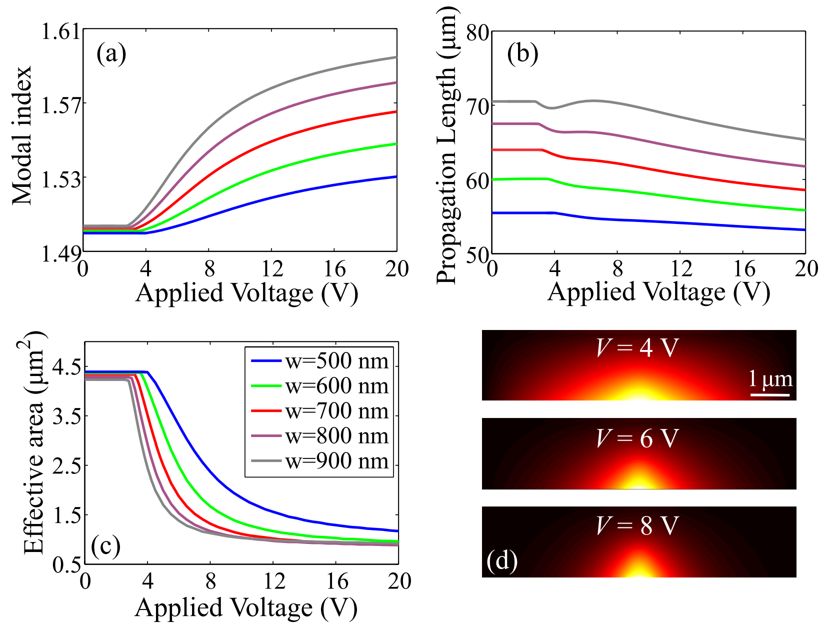
PACS: 42.82.Et, 78.68.+m, 42.70.Df





LC dielectric loaded SPP optical switches (DL2)

Photonics and Nanostructures (2012) at press

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D. C. Zografopoulos[a,*], R. Beccherelli[a], A. C. Tasolamprou[b], and E. E. Kriezis[b]

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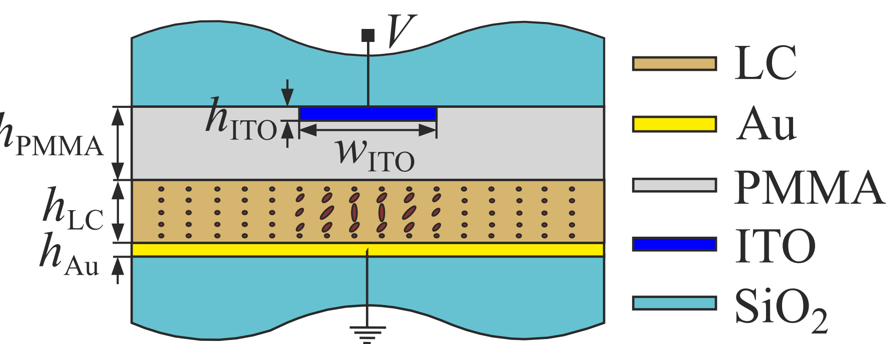

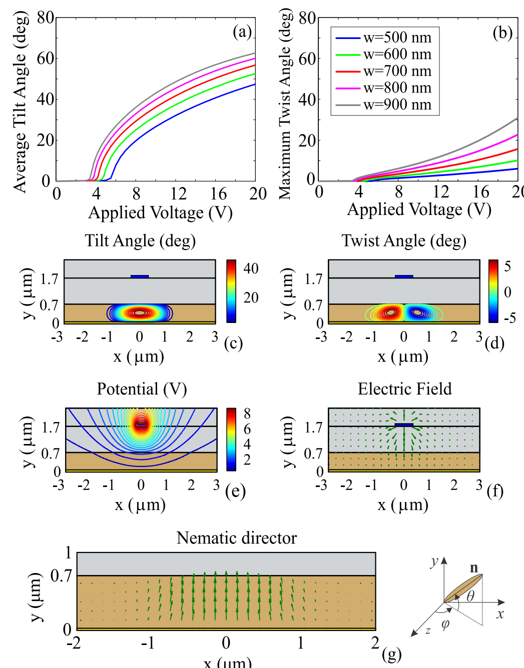

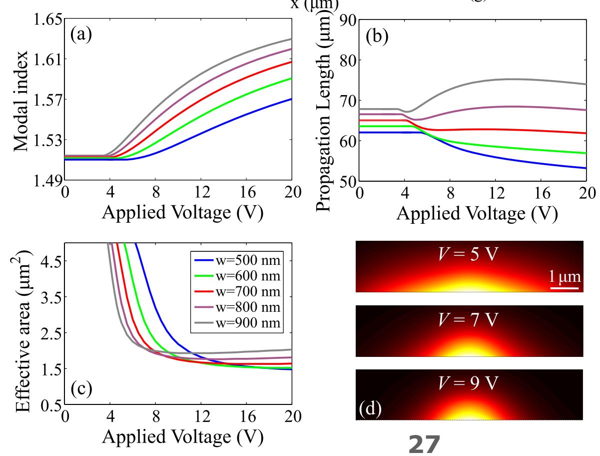

LC Channel Plasmon Polariton optical switches (DL2)

Photonics and Nanostructures (2012) at press

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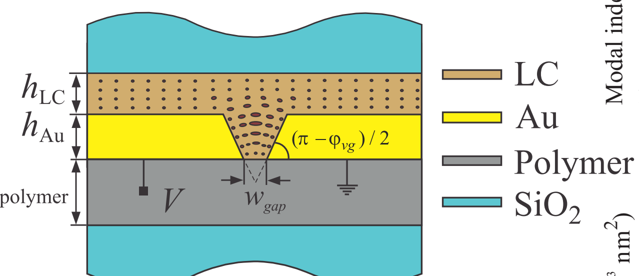

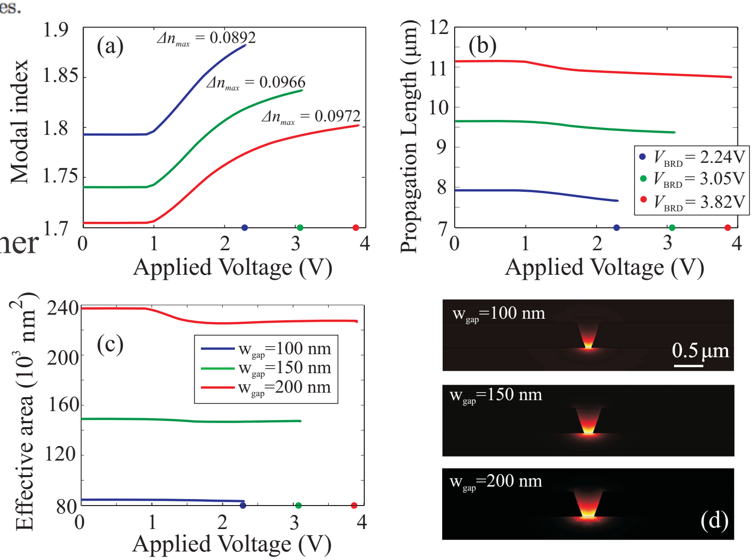

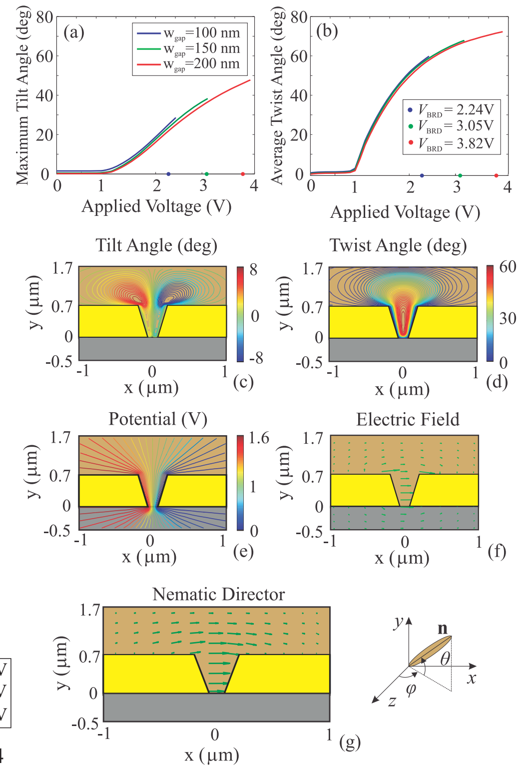

Liquid crystal-based dielectric loaded SPP directional coupler

JOURNAL OF APPLIED PHYSICS **110**, 093102 (2011)

Liquid crystal-based dielectric loaded surface plasmon polariton optical switches

A. C. Tasolamprou,[1,a)] D. C. Zografopoulos,[2,3,b)] and E. E. Kriezis[1,c)]
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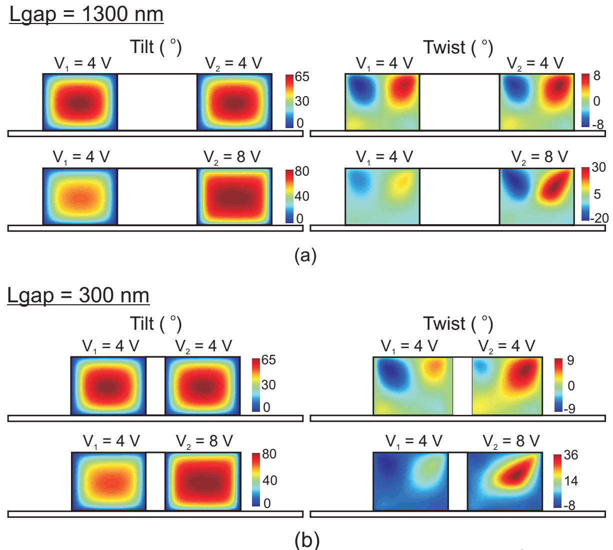

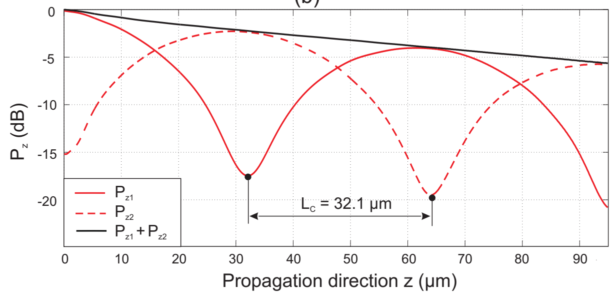

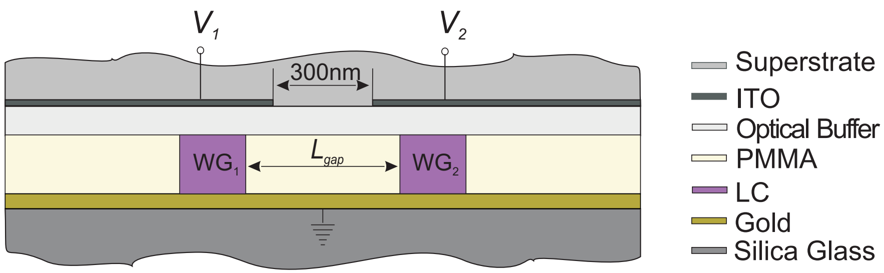

$$P_{BAR} = 1 - \frac{\kappa^2}{\kappa^2 + \frac{\Delta\beta^2}{4}} \sin^2\left(\sqrt{\kappa^2 + \frac{\Delta\beta^2}{4}}\, z\right)$$

$$P_{CROSS} = \frac{\kappa^2}{\kappa^2 + \frac{\Delta\beta^2}{4}} \sin^2\left(\sqrt{\kappa^2 + \frac{\Delta\beta^2}{4}}\, z\right)$$

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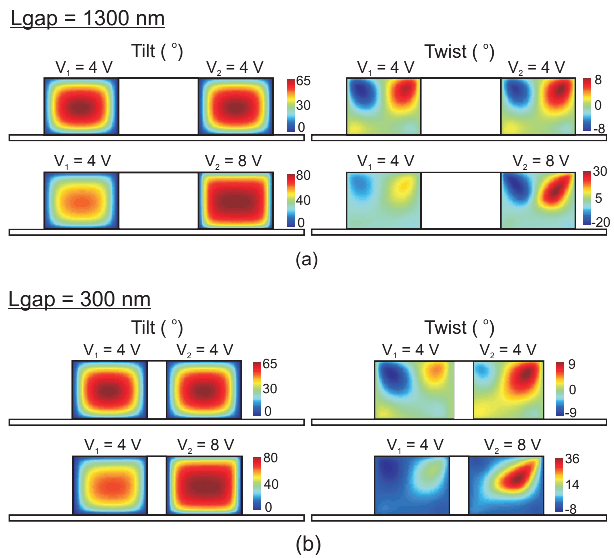

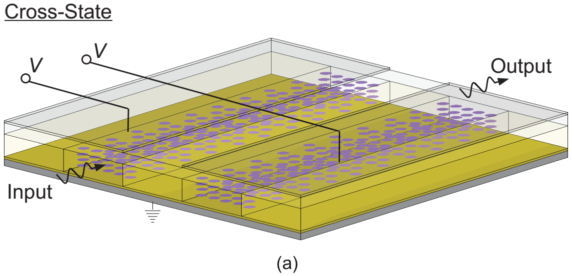

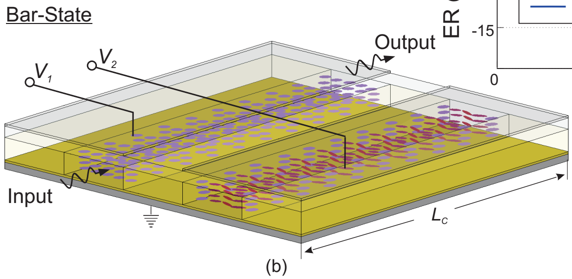

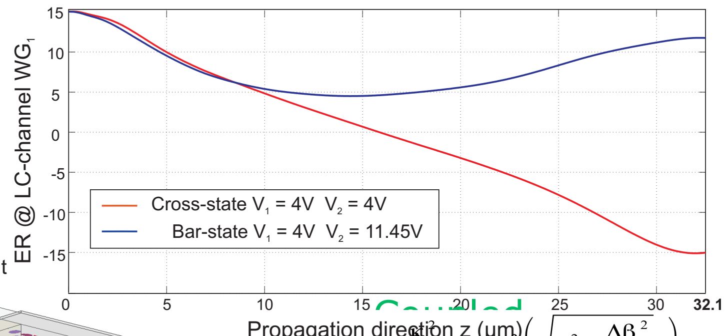

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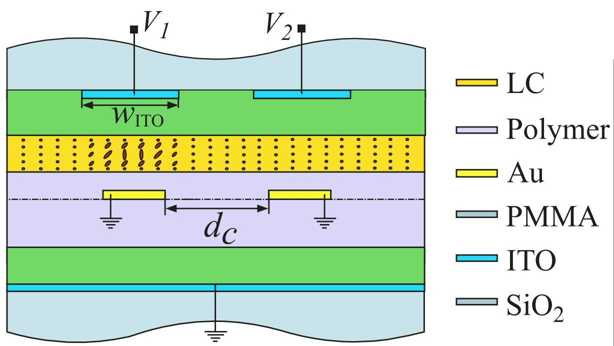
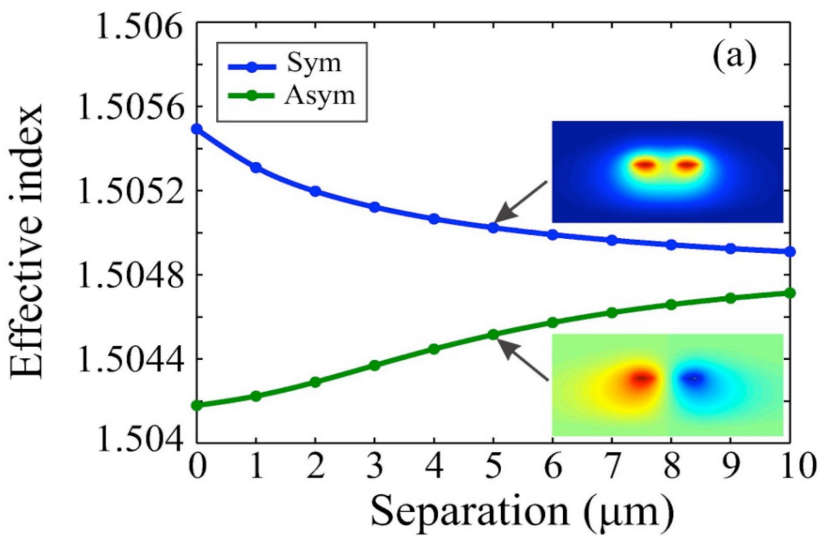
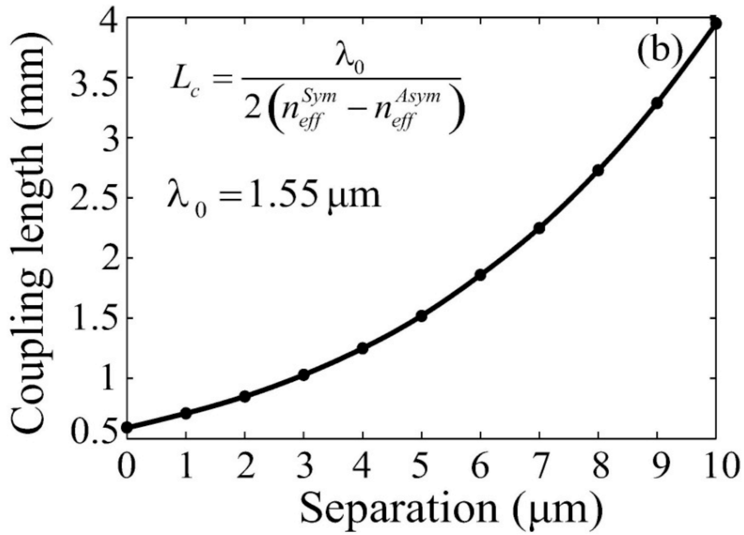
LC-LRSPP: Directional coupler switch (1)



Two LC-LRSPP waveguides are side-coupled: individually addressed by voltages V_1 and V_2

When $V_1=V_2=0$, the coupling length is adjusted by the separation d_C between the two gold stripes





D. C. Zografopoulos, R. Beccherelli, (unpublished)

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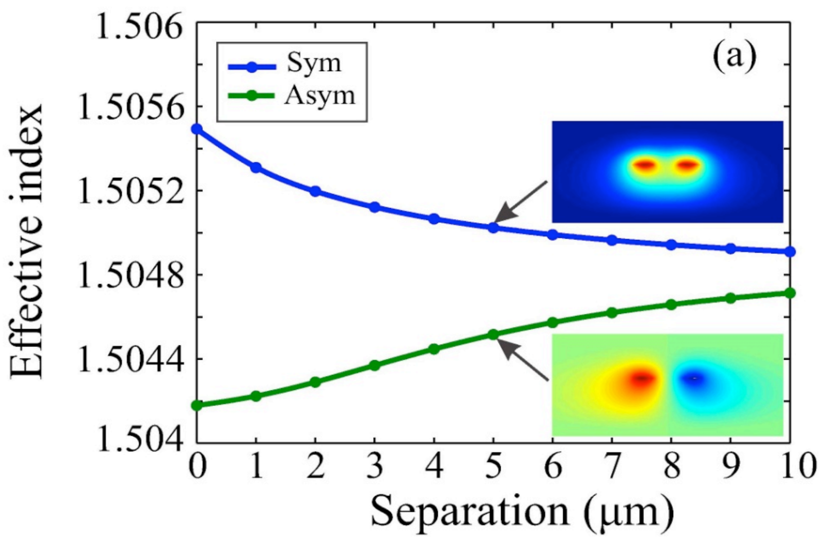
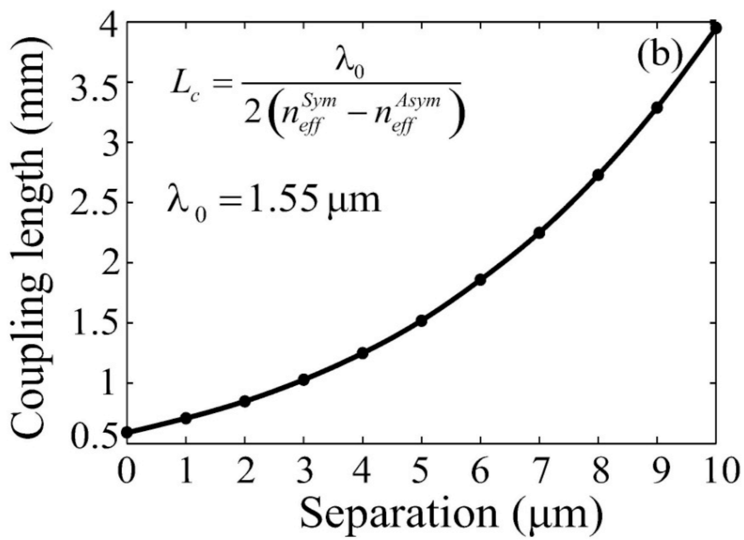
When $V_1=V_2=0$, the coupling length is adjusted by the separation d_C between the two gold stripes



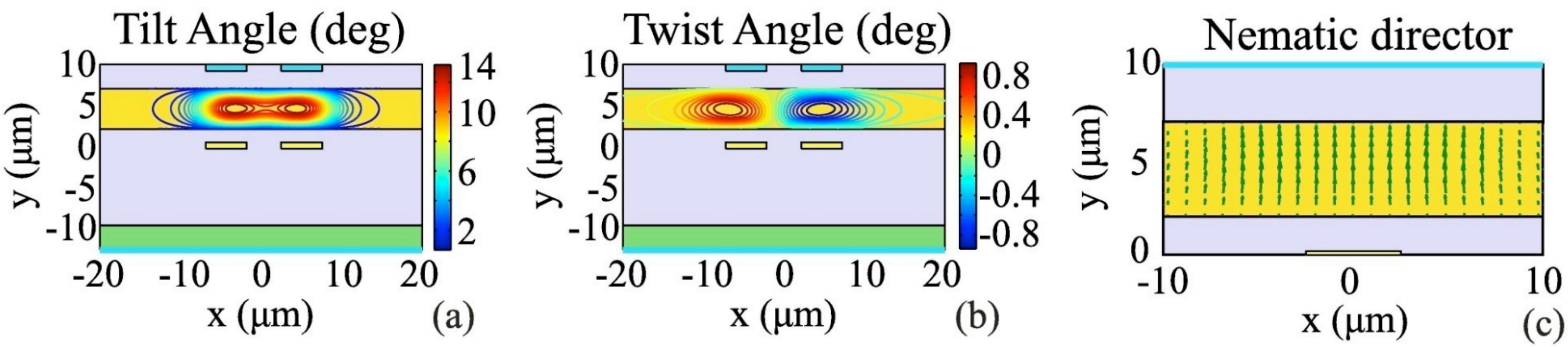


D. C. Zografopoulos, R. Beccherelli, (unpublished)

LC-LRSPP: Directional coupler switch (2)

When V_1=V_2=V, the LC molecules are symmetrically switched above both waveguides

Two identical LC-dielectric waveguides are formed in the two high-tilt zones



By raising the applied voltage V the supermodes of the directional coupler are no longer LR-SPP modes, but hybrid LRSPP-LC ones.

D. C. Zografopoulos, R. Beccherelli, (unpublished)

LC-LRSPP: Directional coupler switch (3)

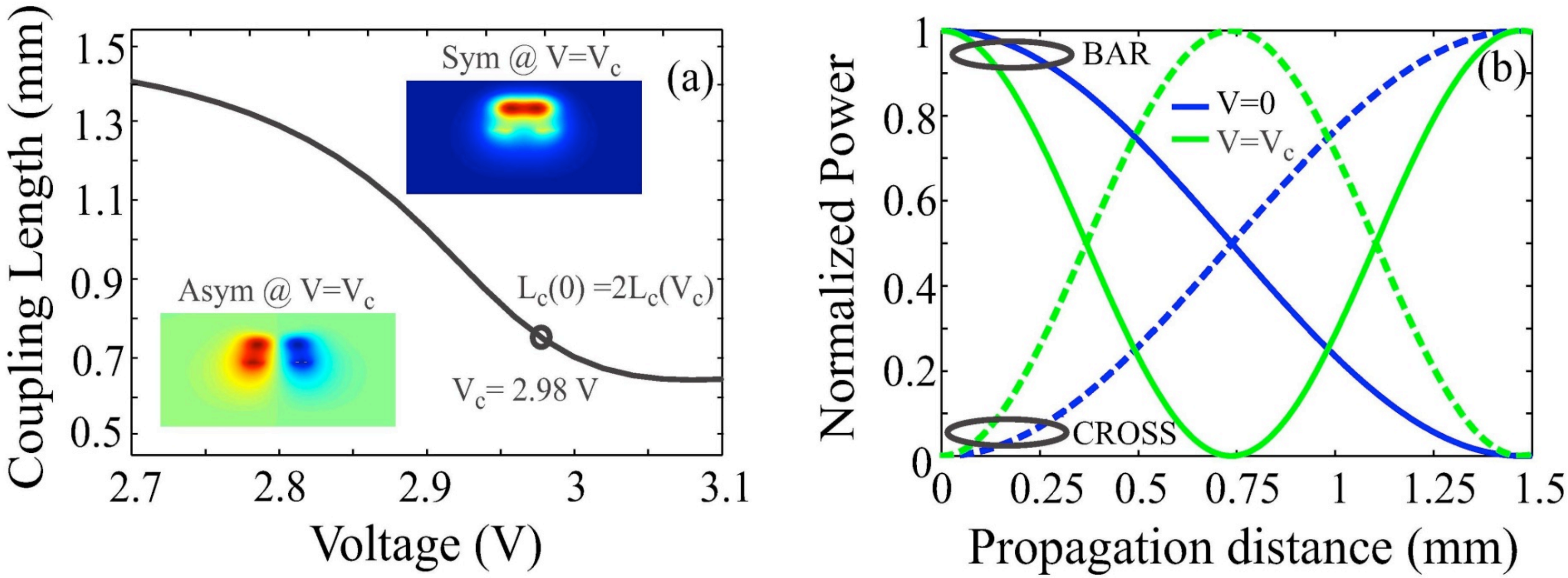
When $V_1=V_2=V$, the coupling length above voltage threshold depends on V

Switching operation is achieved when operating between $V_a=0$ and V_c such that $L_{c,0} = 2L_{c,Vc}$

Coupled Mode Theory*

$$P_{BAR} = \cos^2(\kappa z) \qquad P_{CROSS} = \sin^2(\kappa z) \qquad \kappa = \frac{\pi\left(n_{eff}^{Sym} - n_{eff}^{Asym}\right)}{\lambda_0}$$

$\kappa=\kappa(V)$: coupling coefficient



D. C. Zografopoulos, R. Beccherelli, (unpublished)

* Losses neglected (~ 4 dB/cm)

LC-LRSPP: Directional coupler switch (4)

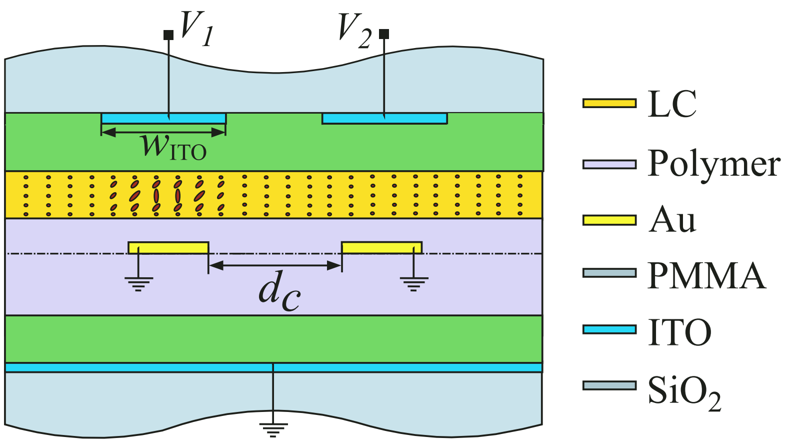
A second approach towards a directional coupler switch: control of the output state via de-synchronization of a single waveguide

Voltage is applied only to one of the two waveguides, $V_1=V$, $V_2=0$

Coupled Mode Theory

$$P_{BAR} = 1 - \frac{\kappa^2}{\kappa^2 + \frac{\Delta\beta^2}{4}} \sin^2\left(\sqrt{\kappa^2 + \frac{\Delta\beta^2}{4}}\, z\right)$$

$$P_{CROSS} = \frac{\kappa^2}{\kappa^2 + \frac{\Delta\beta^2}{4}} \sin^2\left(\sqrt{\kappa^2 + \frac{\Delta\beta^2}{4}}\, z\right)$$



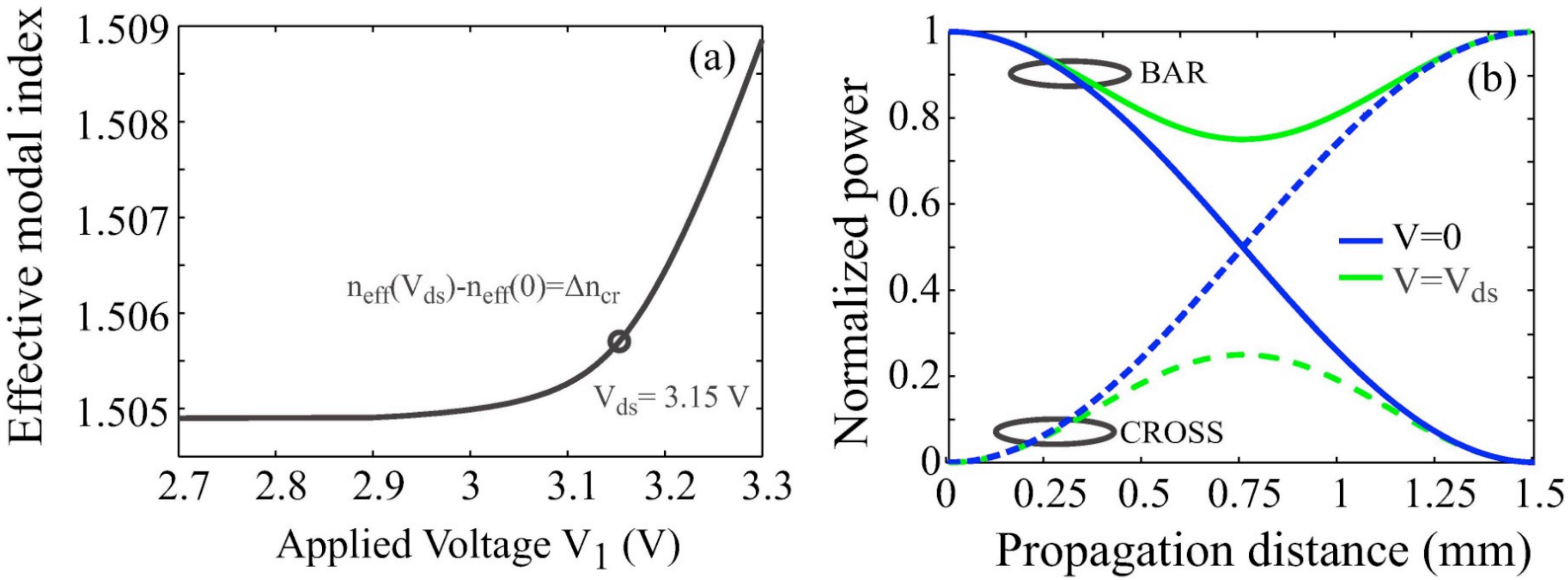
D. C. Zografopoulos, R. Beccherelli, (unpublished)

$\Delta\beta=(2\pi/\lambda)*\Delta n$: desynchronization parameter owing to different modal indices in adjacent waveguides

LC-LRSPP: Directional coupler switch (5)

When the applied voltage V_{ds} introduces the critical phase mismatch…

$$\Delta\beta = \Delta\beta_{cr} = \sqrt{3}\pi / L, \qquad L = \pi / 2\kappa$$



… switching of the cross-bar states is achieved at a distance $L=L_{c,sync}$ of the coupler

D. C. Zografopoulos, R. Beccherelli, (unpublished)

Conclusions

- *Plasmon Polariton based waveguides require tradeoff between cm long propagation suitable for inter-chip and inter-board optical interconnects and sub-wavelength suitable for intra-chip communications*
- *Data level switching may be promising, but there is still a lot of work ahead (absorption) or the mechanisms are incompatible with CMOS process*
- *Various switching mechanisms may be used for circuit level reconfigurations*
- *Power budget may be the ruling factor for dense parallel data buses. Tradeoffs between compactness and propagation losses*
- *Thermal tuning appears limited by power requirements (10s mW per line), which also affects line density*
- *Liquid crystals can tune LR-SPP, DL-SPP and CPP, typically with a transverse duty cycle of ≈50%, CMOS compatible low voltage and negligible power*
- *Voltage controlled LC attenuators or ON-OFF switches depending on LC choice*
- *Voltage controlled LC directional couplers for LR-SPP DL-SPP*

Thank you for your attention

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