Surface wave resonance

and optical sensing

Muhammad Faryad

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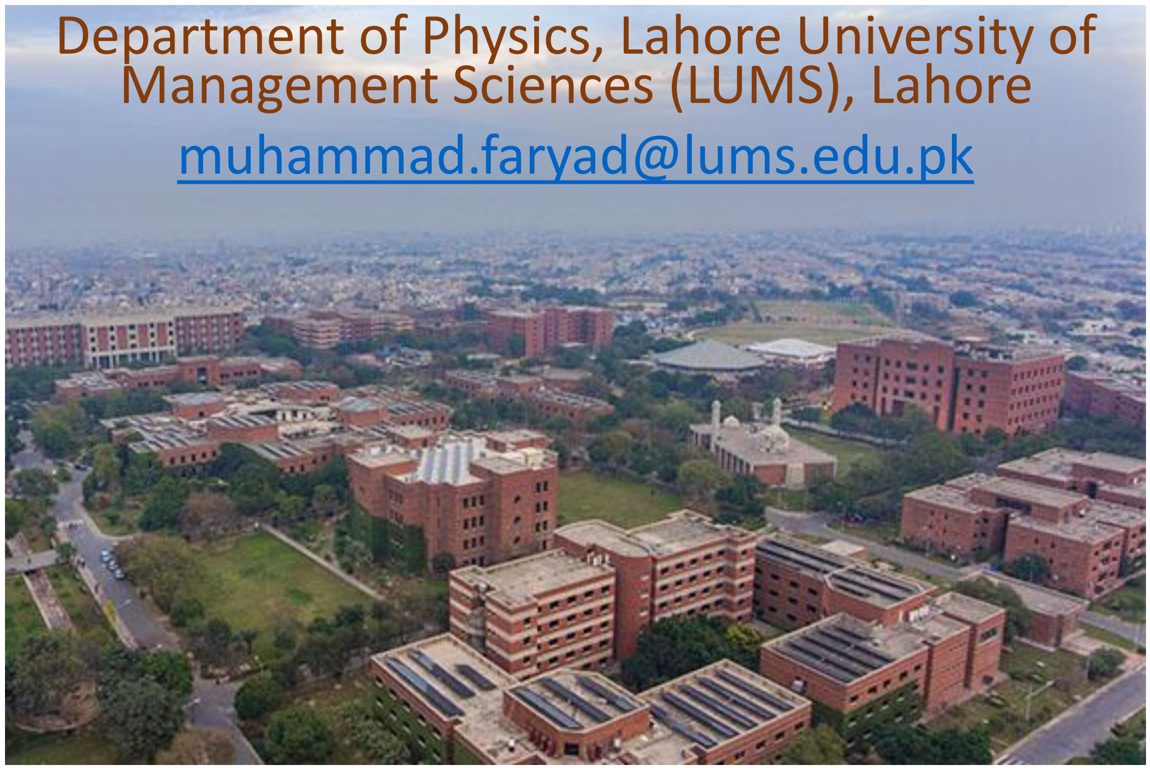
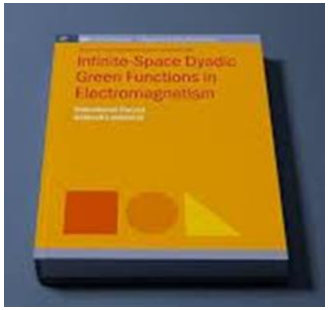
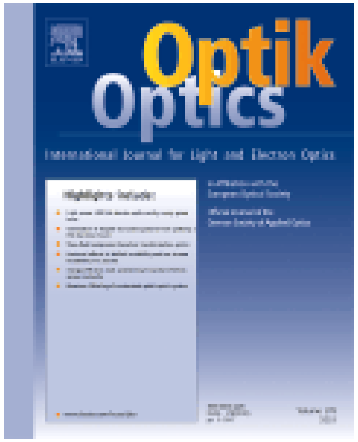


Abdus Salam International Center of Theoretical Physics, 2019

My research is focused on interaction of light with anisotropic, nonhomogeneous materials

- Nanostructured plasmonic solar cells
- Dyadic Green functions (Basic solutions of Maxwell equations in anisotropic mediums)
- Optics of one-dimensional photonic crystals
- Hyperbolic, zero-index, negative-phase velocity, metamaterials
- Surface plasmon-polariton waves guided by sculptured thin films
- Plasmonic optical sensor





Optics/Photonics outreach activities

- Optics School
- Optics lab being developed under HEC grant
- Outreach activities at primary/middle schools
- Active SPIE student chapter
- Seminars at ITU, Punjab University, Faisalabad Agriculture
- 4-days short course on plasmonics, 2014 (QAU)
- Nathiagalli invited speaker on plasmonics, 2014, 2015
- 4-days workshop on optics of anisotropic media (QAU), 2019

SPIE. STUDENT CHAPTER
LAHORE UNIVERSITY OF MANAGEMENT SCIENCES (LUMS)

Outline

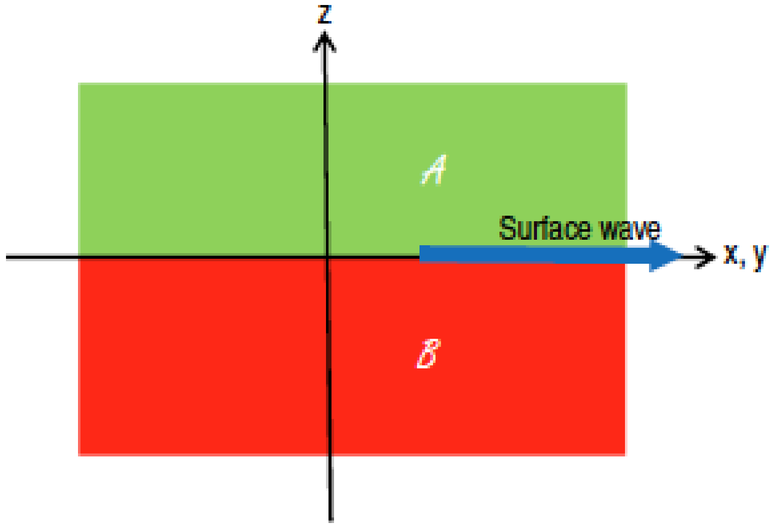
- Canonical boundary-value problem of surface wave propagation
  - Dispersion equation
  - Numerical examples

- Prism-coupled problem for excitation of surface waves
  - SPP waves
  - Dyakonov—Tamm waves
  - Tamm waves
  - Uller—Zenneck waves

- Optical sensing

Surface waves

are guided by
an interface of two dissimilar materials

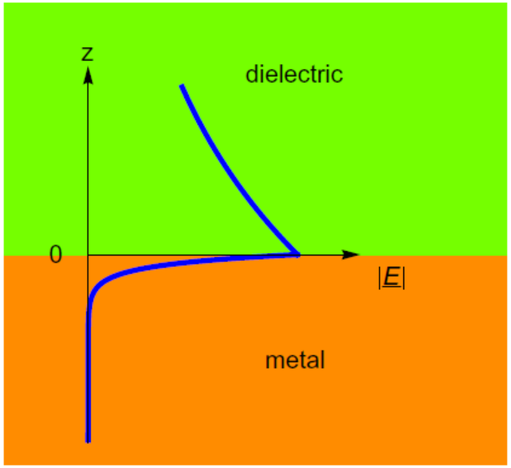


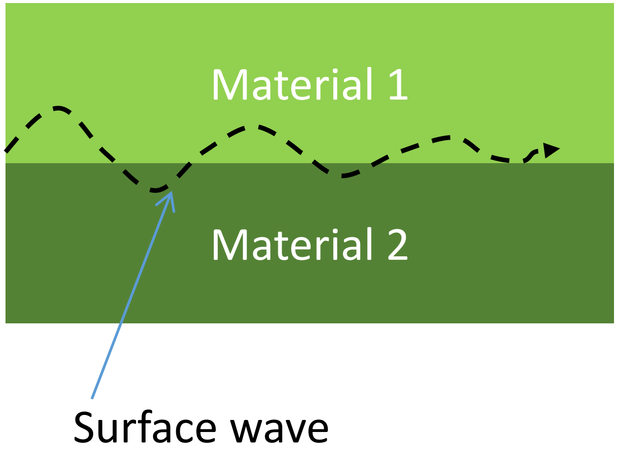
Surface plasmon-polariton (SPP) waves

Bound to an interface of a metal and a dielectric material

Sensitive to changes in constitutive properties near interface

Wavelength of surface wave is (usually*) shorter than in either of the bulk materials



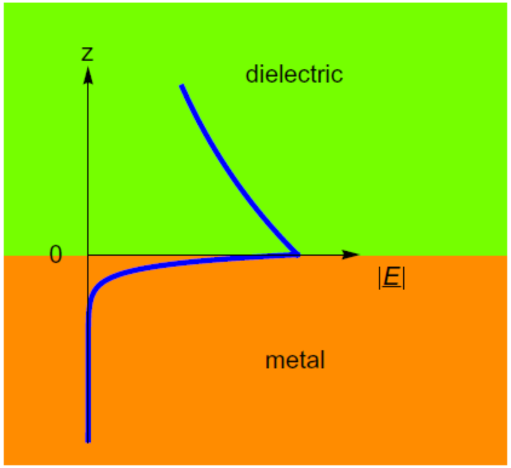


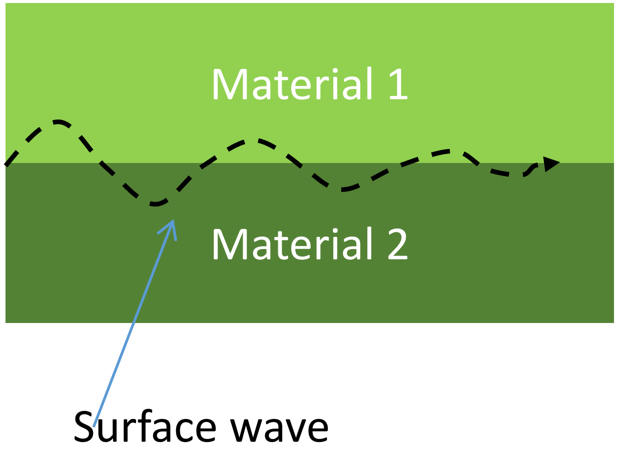
Applications of SPP waves

Chemical sensors

Communication

Solar cells



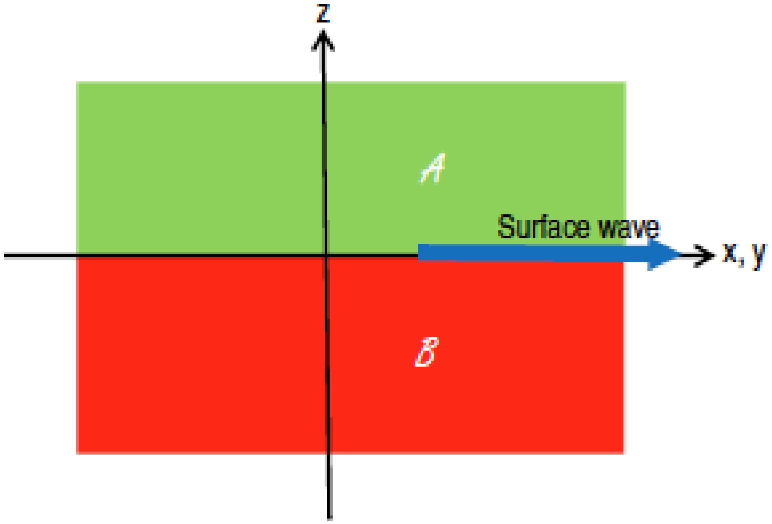


Taxonomy of surface waves

- Surface plasmon-polariton (SPP) waves ---metal/dielectric interface
- Dyakonov waves ---anisotropic-dielectric/dielectric interface
- Tamm waves ---isotropic-dielectric/isotropic-dielectric interface with one material being periodically nonhomogeneous
- Dyakonov—Tamm waves ---anisotropic-dielectric/dielectric interface with anisotropic dielectric being periodically nonhomogeneous
- Uller—Zenneck waves---the interface of two homogeneous dielectric material materials with at least on being lossy

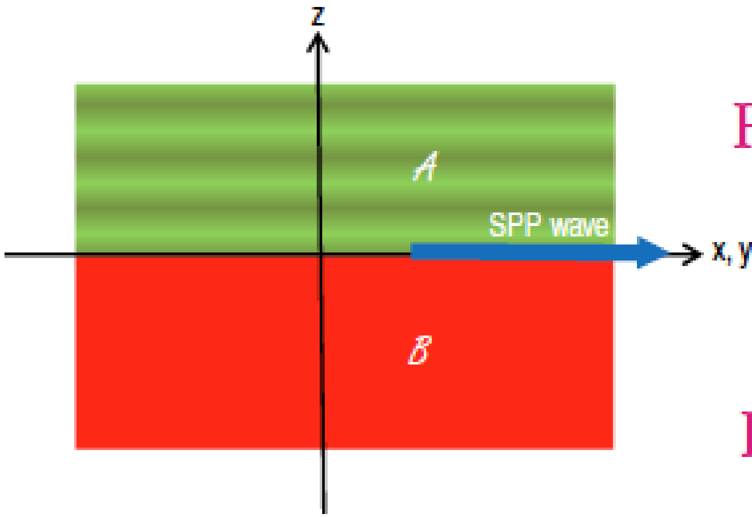
Surface waves

are electromagnetic waves that



1. satisfy Maxwell equations in both materials,
2. satisfy boundary conditions at the interface, and
3. their fields must decay away from the interface

Surface plasmon-polariton (SPP) wave



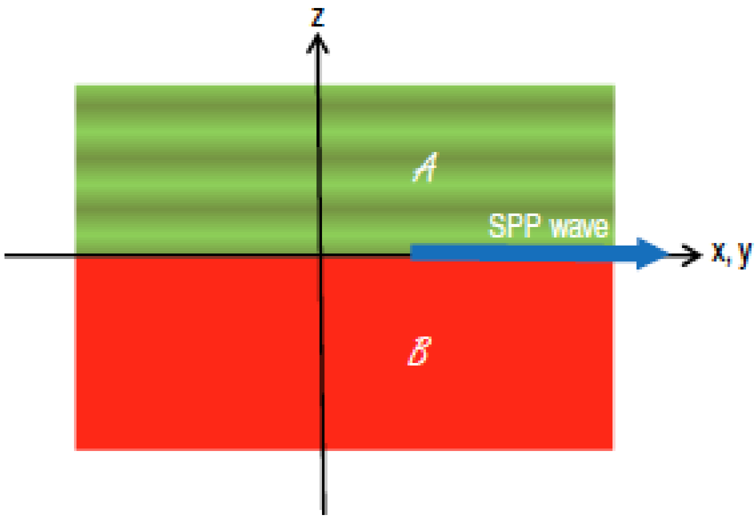
Material A: dielectric

$$\mathrm{Re}\left[\epsilon^{\mathcal{A}}_{\alpha\beta}(z)\right] > 0\,, \quad \mathrm{Im}\left[\epsilon^{\mathcal{A}}_{\alpha\beta}(z)\right] \simeq 0$$

Material B: metal

$$\mathrm{Re}\left(\epsilon^{\mathcal{B}}\right) < 0\,, \quad \mathrm{Im}\left(\epsilon^{\mathcal{B}}\right) > 0$$

Canonical boundary-value problem



A few numerical results

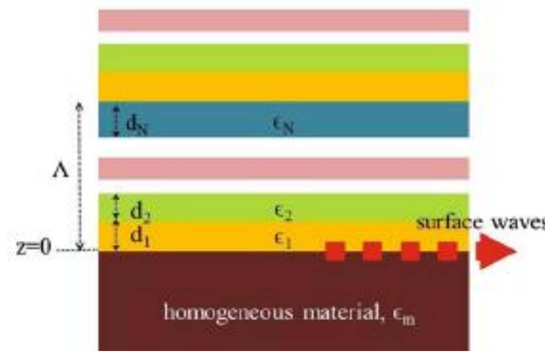
Canonical Boundary-Value Problem

Applied Physics A (2018) 124:102
https://doi.org/10.1007/s00339-017-1527-8

Applied Physics A
Materials Science & Processing

Differentiating surface plasmon-polariton waves and waveguide modes guided by interfaces with one-dimensional photonic crystals

Muhammad Faryad[1]



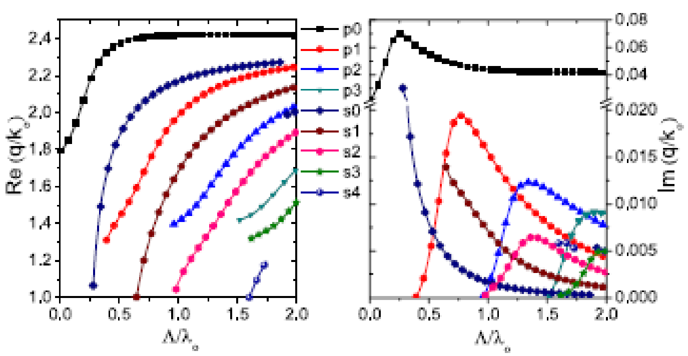


Fig. 3 *SPP waves* (left) Real and (right) imaginary of parts of the relative wavenumbers q/k_0 of SPP waves as a function of the period $\Lambda = 2d_1 = 2d_2$ of the PC with two layers of equal thicknesses in each period

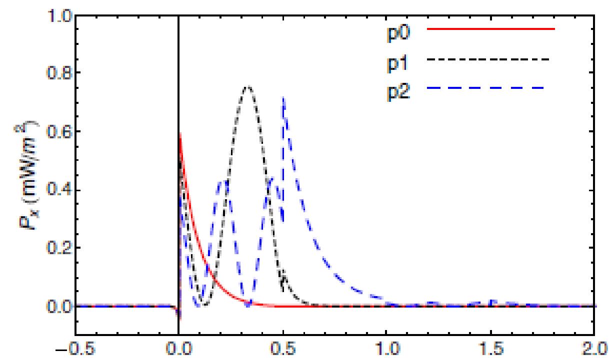


Fig. 5 *Spatial profiles of SPP waves* The x-component of the time averaged Poynting vector **P** of SPP waves guided by the interface of aluminum and a PC with two layers in each period when $\Lambda = 1.2\lambda_0$, $\lambda_0 = 633$ nm. For the computation, $B_m^{(p)} = 1$ and $B_m^{(s)} = 1$ V/m was set for p- and s-polarized SPP waves, respectively. The vertical black lines at $z = 0$ indicate the position of the metal/PC interface. The vertical axis has units of milliwatts per meter square

Contents lists available at ScienceDirect

Optics Communications

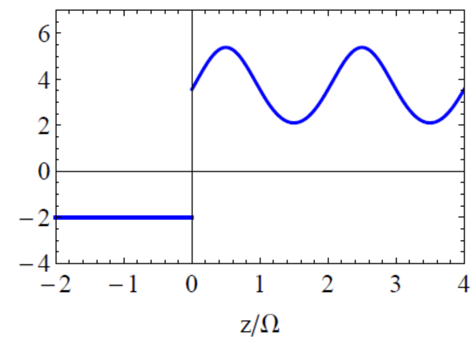
journal homepage: www.elsevier.com/locate/optcom

Multiple surface plasmon–polariton waves guided by the interface of a metal and a periodically nonhomogeneous magnetic material

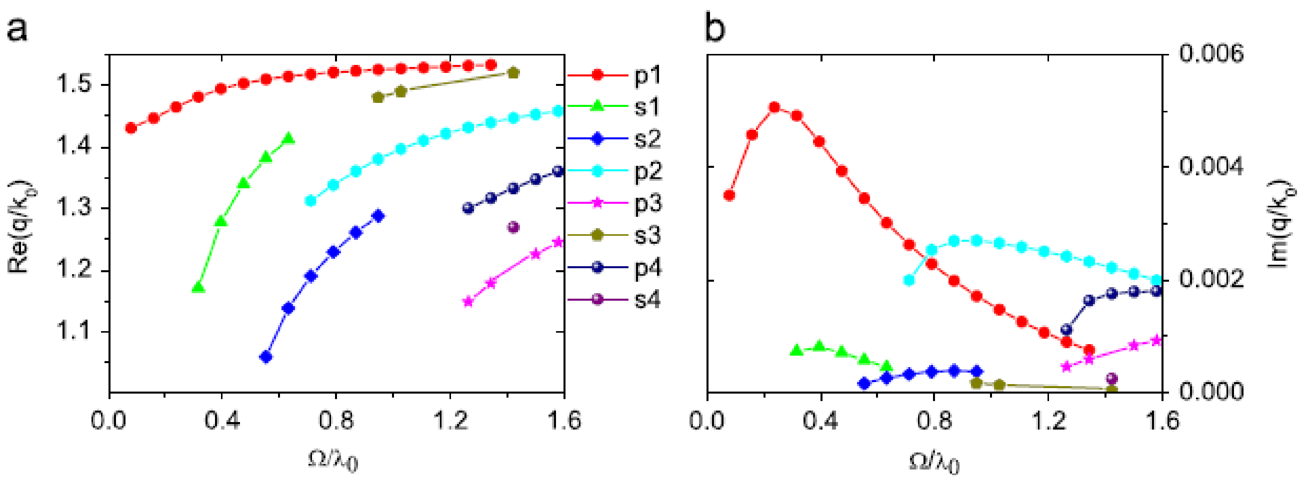
Farhat Abbas [a], Qaisar A. Naqvi [a], Muhammad Faryad [b,*]

[a] Department of Electronics, Quaid-i-Azam University, Islamabad 45320, Pakistan
[b] NanoMM–Nanoengineered Metamaterials Group, Department of Engineering Science and Mechanics, Pennsylvania State University, University Park, PA 16802, USA

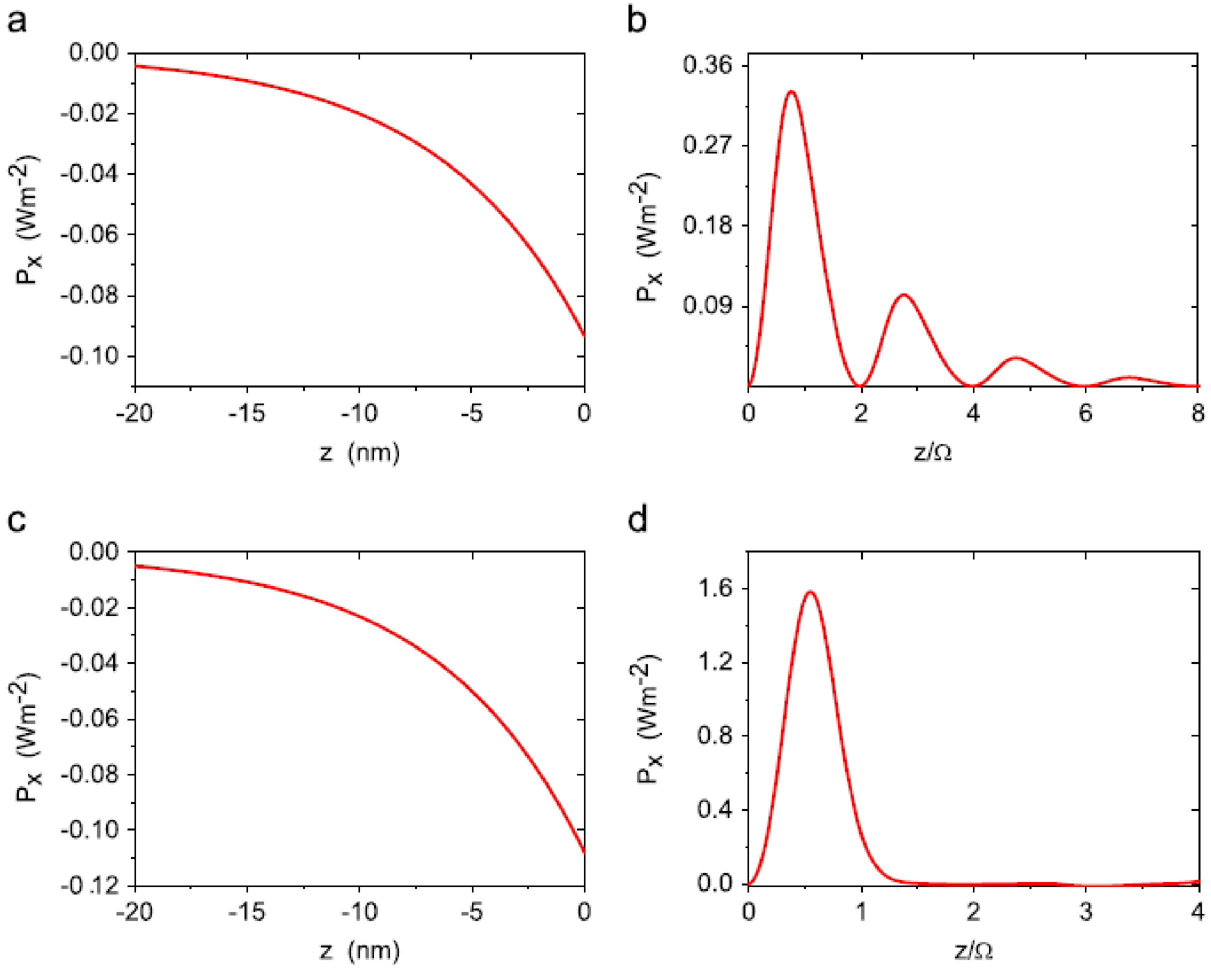
$$\mu_r(z) = \left[\mu_{avr} + \Delta_\mu \sin\left(\pi \frac{z}{\Omega}\right)\right],$$



$\lambda_0 = 633$ nm, $\epsilon_r = 1$, $\mu_{avr} = 2$, and $\Delta_\mu = 0.5$.



Field profiles are in accordance with Floquet theory

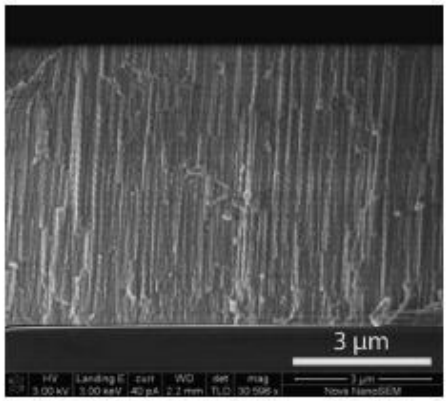


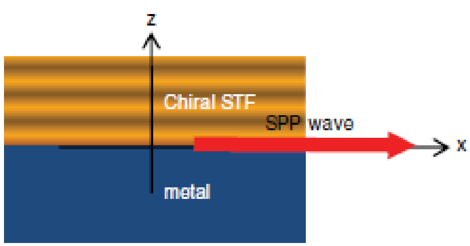
(a) $\Omega = 0.394\lambda_0(s1)$, (b) $\Omega = 0.394\lambda_0(s1)$, (c) $\Omega = 0.947\lambda_0(s3)$, (d) $\Omega = 0.947\lambda_0(s3)$.

Research Article Vol. 34, No. 9 / September 2017 / Journal of the Optical Society of America B 1937

Multiple surface-plasmon-polariton waves guided by a chiral sculptured thin film grown on a metallic grating

Sema Erten,[1] Muhammad Faryad,[2] and Akhlesh Lakhtakia[1,*]





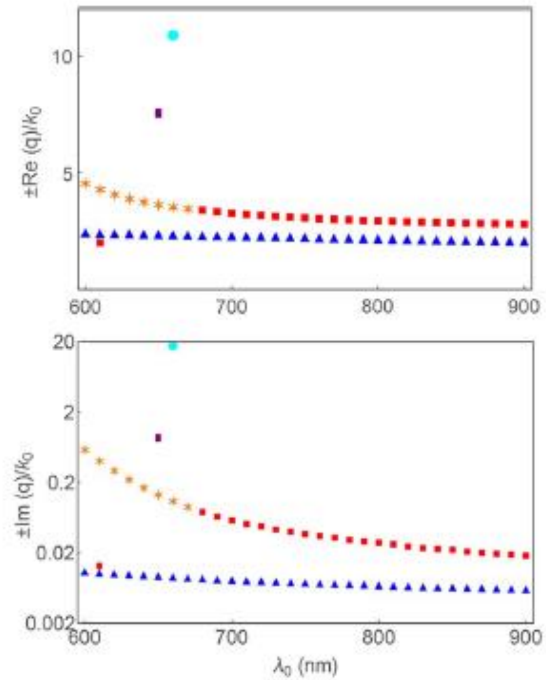
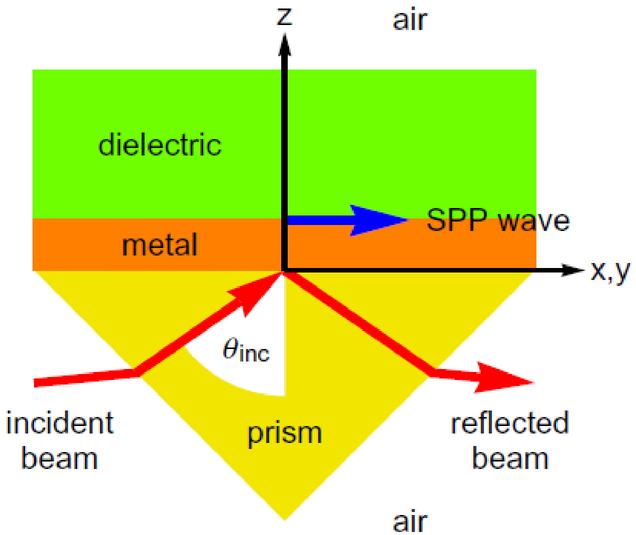
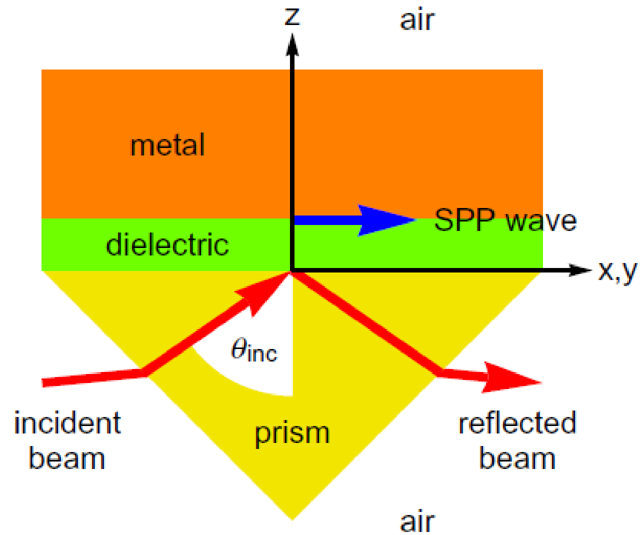


Fig. 4. Real and imaginary parts of the calculated relative wavenumbers of SPP waves propagating parallel to $\pm\mathbf{u}_x$. The constitutive parameters of the metal and the chiral STF are provided at the beginning of Section 2.D.

Prism-coupled configuration



Turbadar—Kretschmann—Raether



Turbadar—Otto

A few examples

Prism-coupled configurations

Optics Communications 284 (2011) 5678–5687

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Optics Communications

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On multiple surface-plasmon-polariton waves guided by the interface of a metal film and a rugate filter in the Kretschmann configuration

Muhammad Faryad, Akhlesh Lakhtakia *

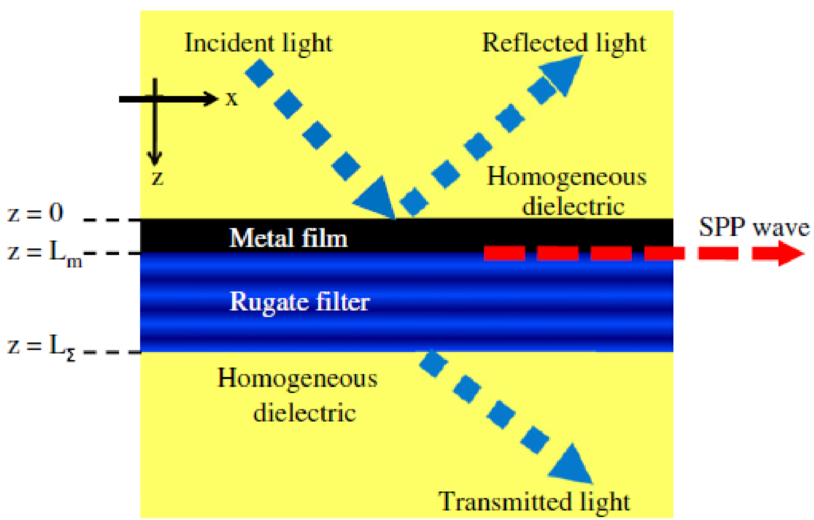


Fig. 1. Schematic of the Kretschmann configuration.

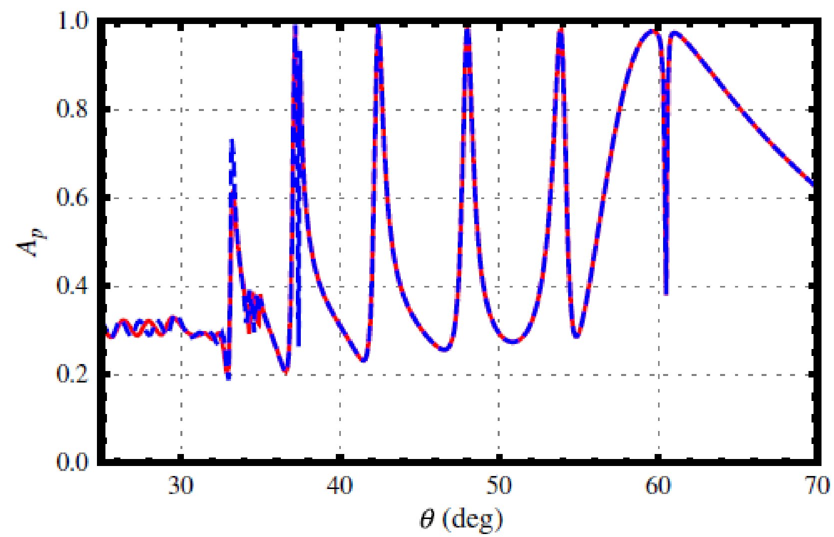
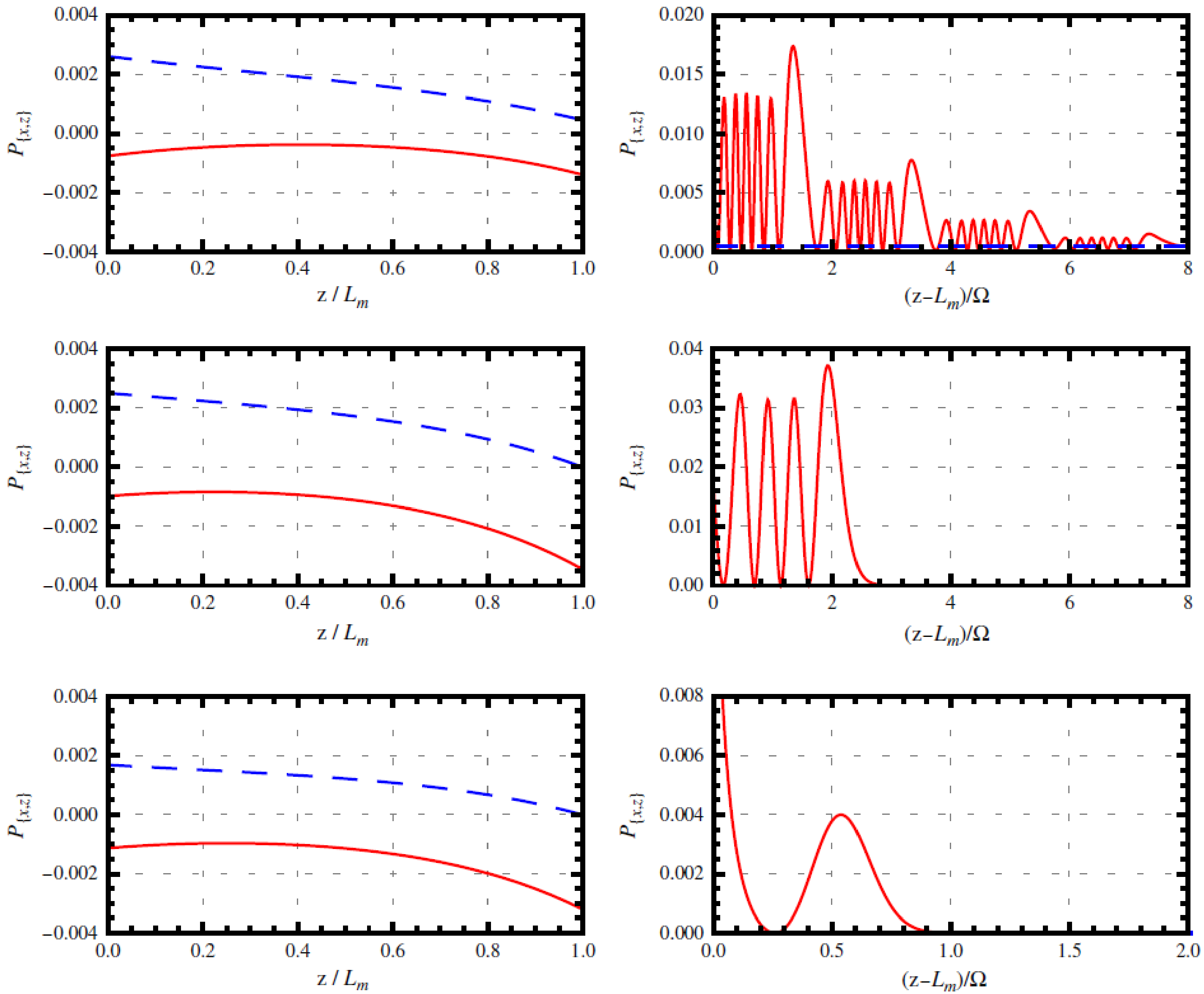


Fig. 3. Absorptance A_p as function of the incidence angle θ in the Kretschmann configuration, when $\lambda_0 = 633$ nm, $n_{\ell} = 2.58$, $L_m = 30$ nm, and $\Omega = 1.5\lambda_0$. Solid red line is for $N_p = 3$ and dashed blue line is for $N_p = 4$. Others parameters are given at the beginning of Section 3.

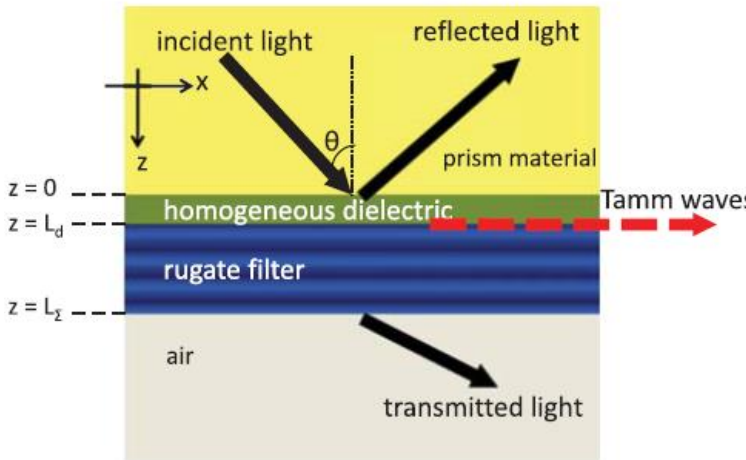


$P_{\{x,z\}}$
z / L_m
$(z-L_m)/\Omega$

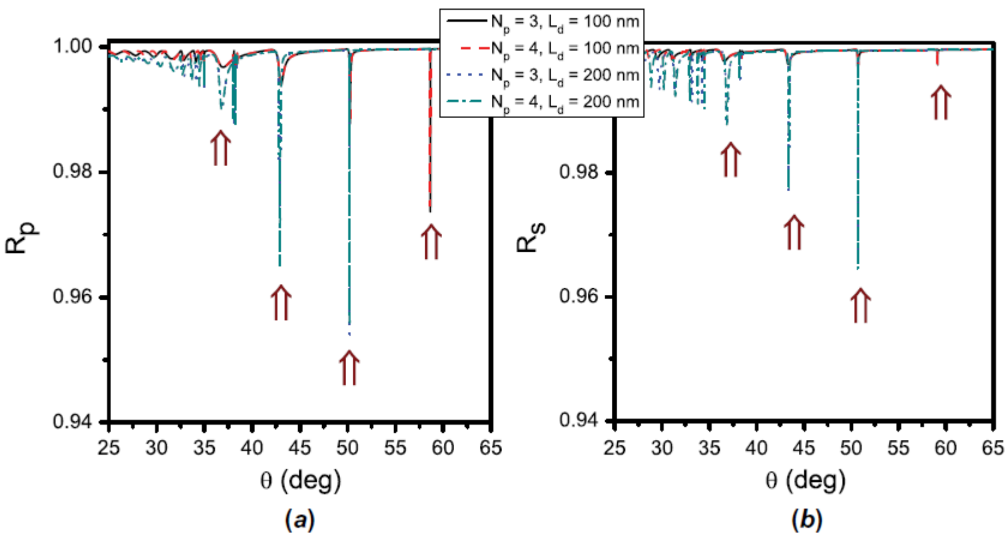
Journal of Modern Optics, 2013

Prism-coupled excitation of multiple Tamm waves

Husnul Maab[a,b], Muhammad Faryad[b*] and Akhlesh Lakhtakia[b]



Sharper reflectance dips for Tamm waves offer more sensitive chemical sensors than SPP waves!



The replacement of the metallic film with the dielectric film means less losses and higher feasibility for integration in optical circuits

Parametric investigation of prism-coupled excitation of Dyakonov–Tamm waves

Drew Patrick Pulsifer, Muhammad Faryad, and Akhlesh Lakhtakia*

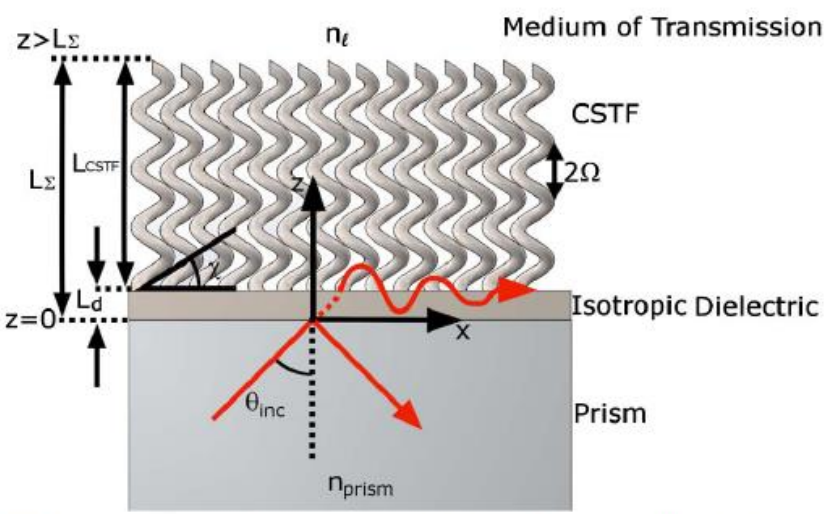
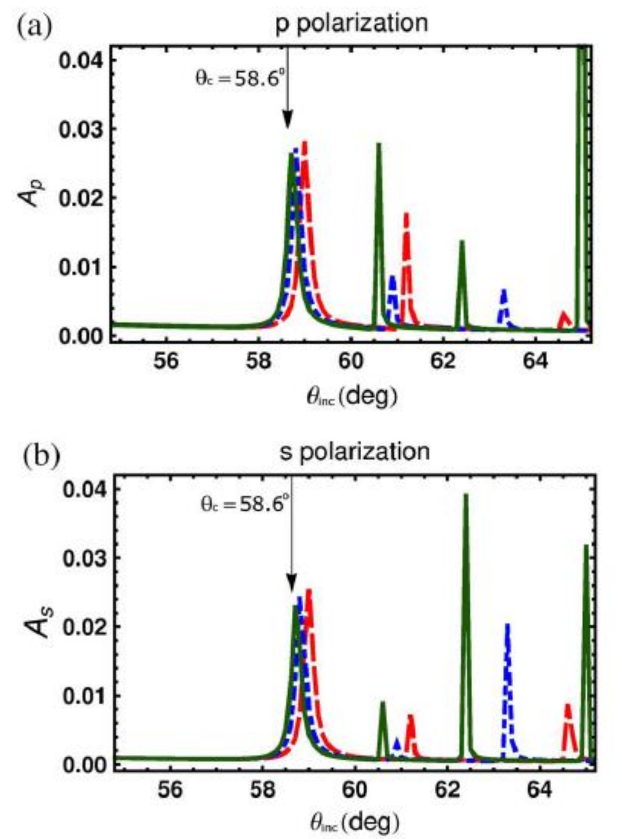


Fig. 1. Schematic of the prism-coupled configuration. The half-space $z < 0$ is occupied by the prism material and the half-space $z > L_\Sigma$ is occupied by another homogeneous isotropic material, both assumed to have negligible dissipation.



Dyakonov–Tamm waves guided by the planar surface of a chiral sculptured thin film

Muhammad Faryad,* Akhlesh Lakhtakia, and Drew Patrick Pulsifer

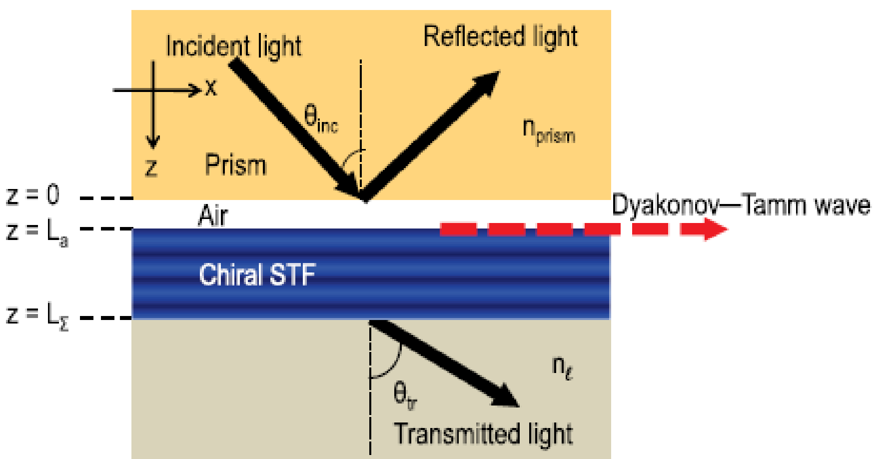
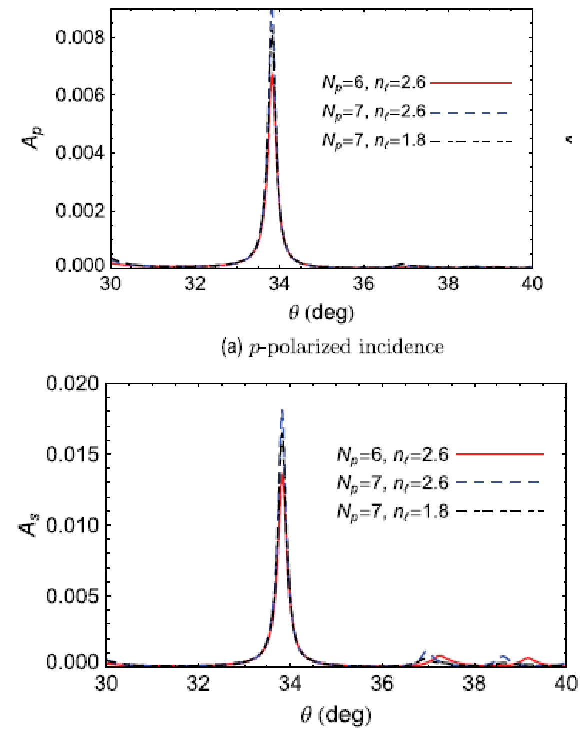


Fig. 5. Schematic of the prism-coupled configuration to study the excitation of the Dyakonov–Tamm waves. Since $n_{\rm prism} \sin\theta_{\rm inc} = n_\ell \sin\theta_{\rm tr}$, $n_{\rm prism} > 0$, $n_\ell > 0$, and $\theta_{\rm inc} \in [0°, 90°)$, it is possible that $\theta_{\rm tr}$ is a complex angle.



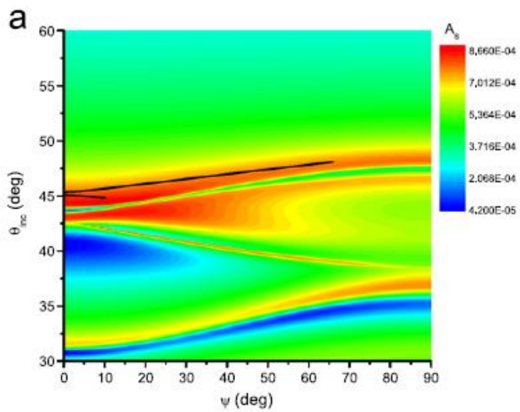
(a) *p*-polarized incidence

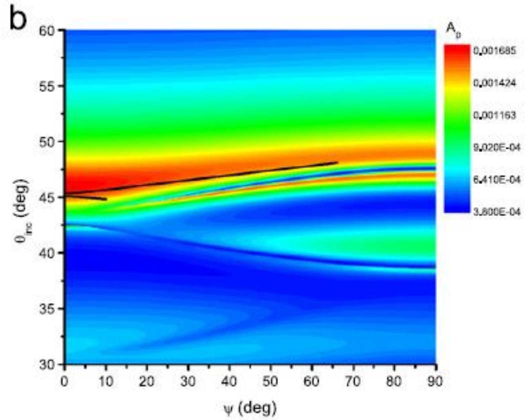
(b) *s*-polarized incidence

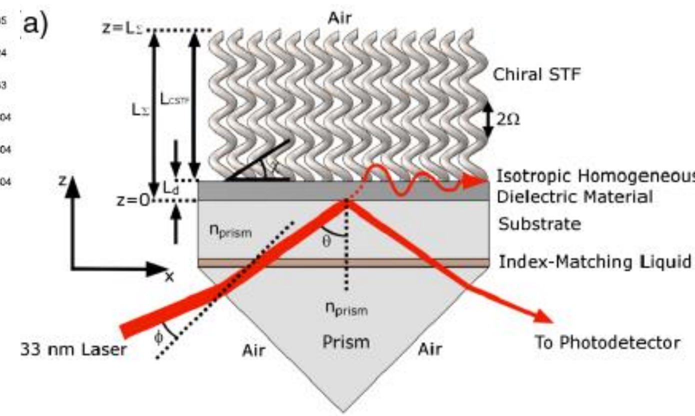
Optics Communications 294 (2013) 192–197

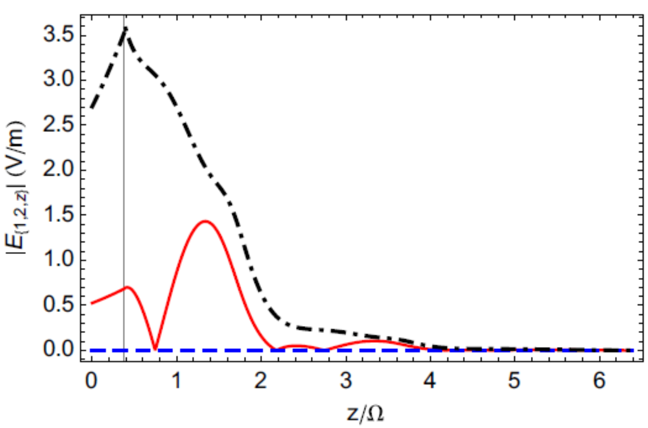
Prism-coupled excitation of Dyakonov–Tamm waves

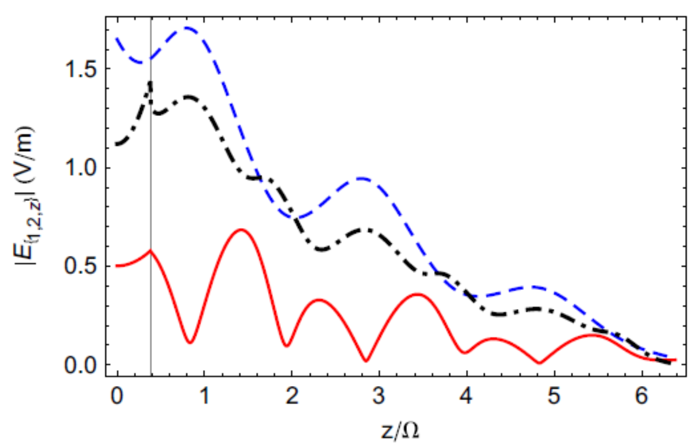
Muhammad Faryad*, Akhlesh Lakhtakia





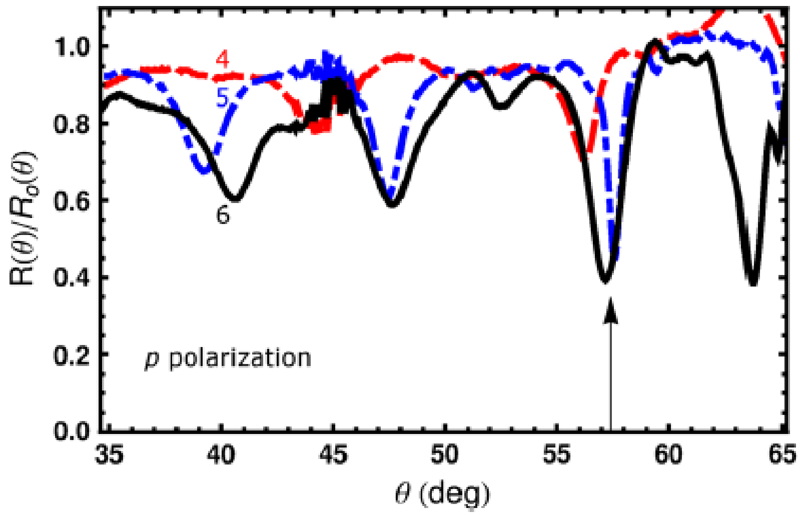


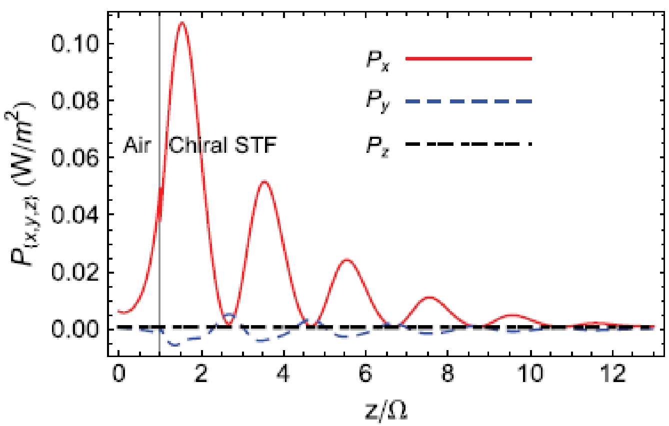


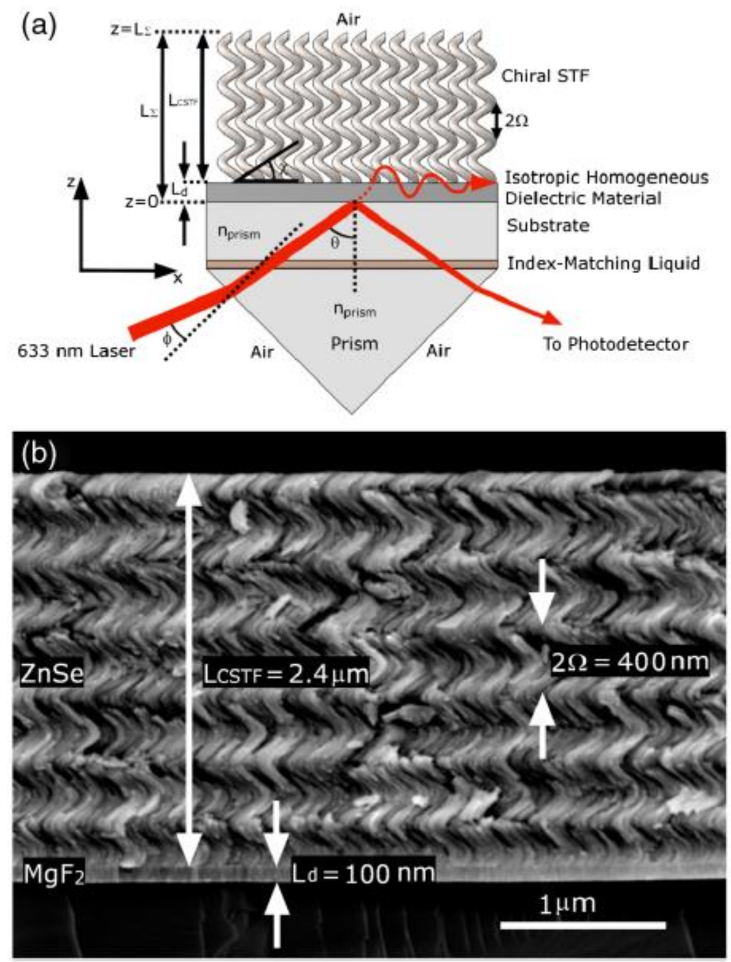


Observation of the Dyakonov-Tamm Wave

Drew Patrick Pulsifer, Muhammad Faryad, and Akhlesh Lakhtakia*



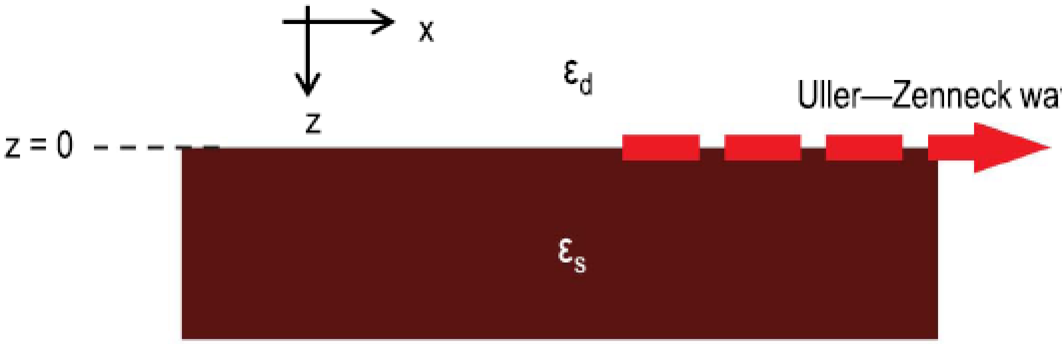




Not all surface waves can be excited in the prism coupled configuration

Uller—Zenneck surface waves

$$q = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_s}{\varepsilon_d + \varepsilon_s}},$$

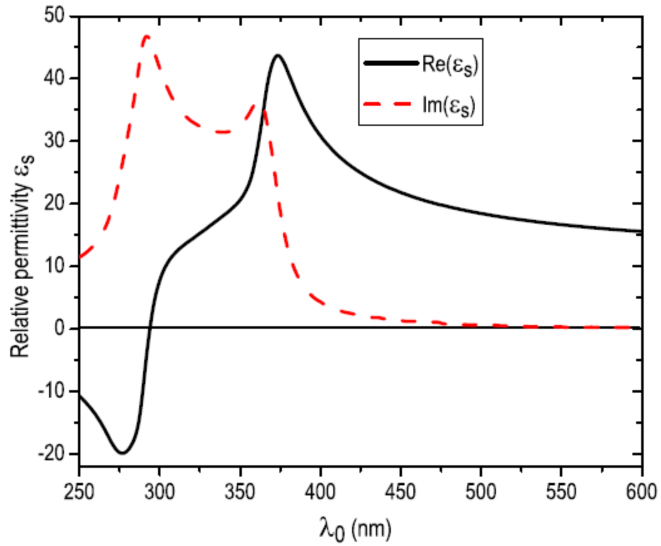


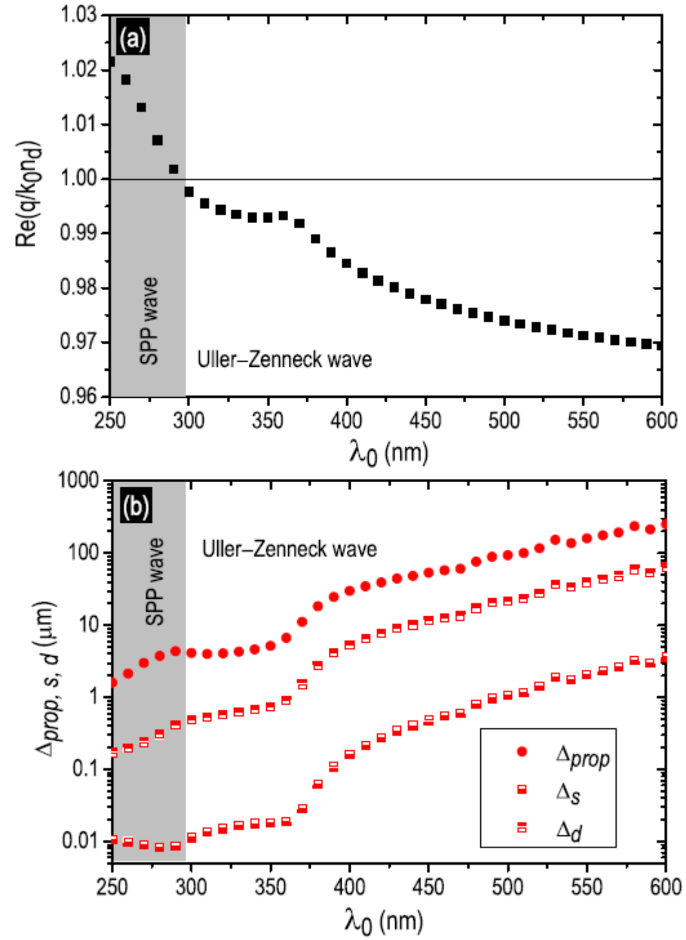
(a) Canonical boundary-value problem

Guided by the interface of two homogeneous dielectric materials!

The first type of surface wave investigated by Uller (1903) and Zenneck (1907)!

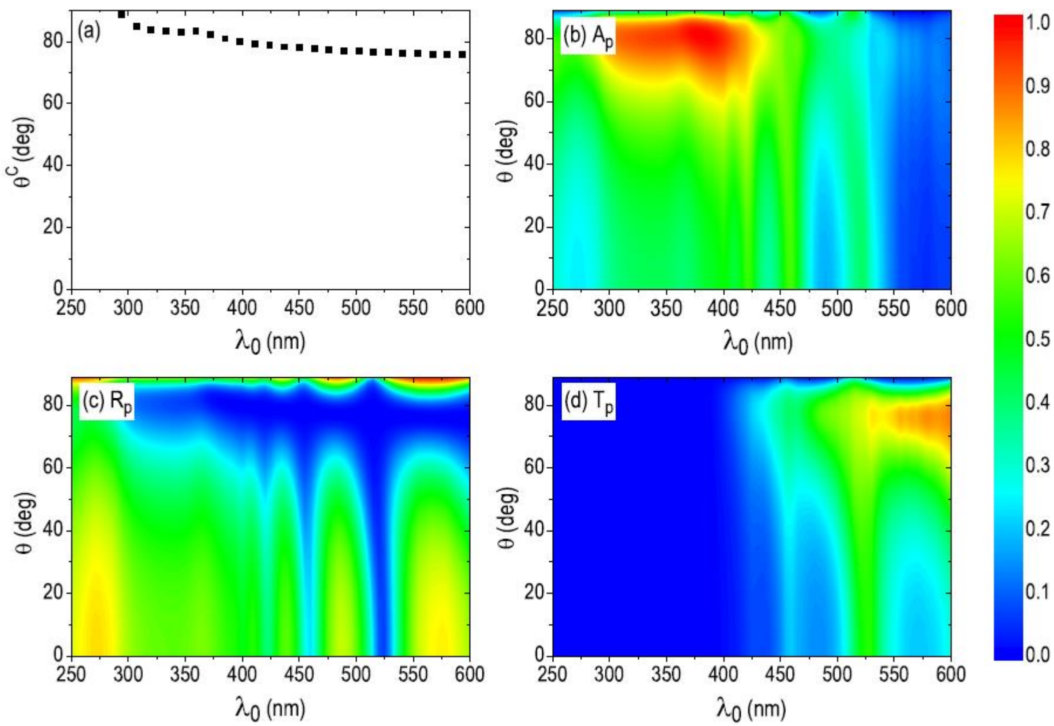
Canonical problem shows the existence of Uller—Zenneck surface waves



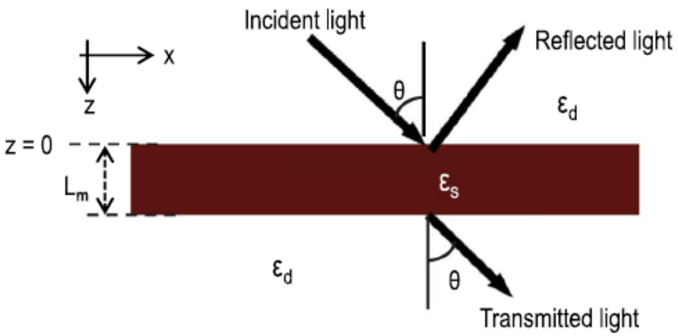


Silicon/air interface

Observation of Uller—Zenneck surface waves with planar interfaces has been problematic



$$\theta^{\mathrm{C}} = \sin^{-1}[\mathrm{Re}(q)/k_0 n_d]$$



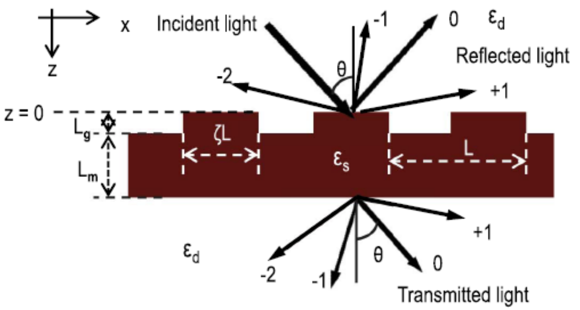
(b) Practical configuration with planar guiding interface

No prism is needed for its excitation as relative wavenumber is less than unity

Grating-coupled excitation of the Uller–Zenneck surface wave in the optical regime

J. Opt. Soc. Am. B / Vol. 31, No. 7 / July 2014

Muhammad Faryad and Akhlesh Lakhtakia*

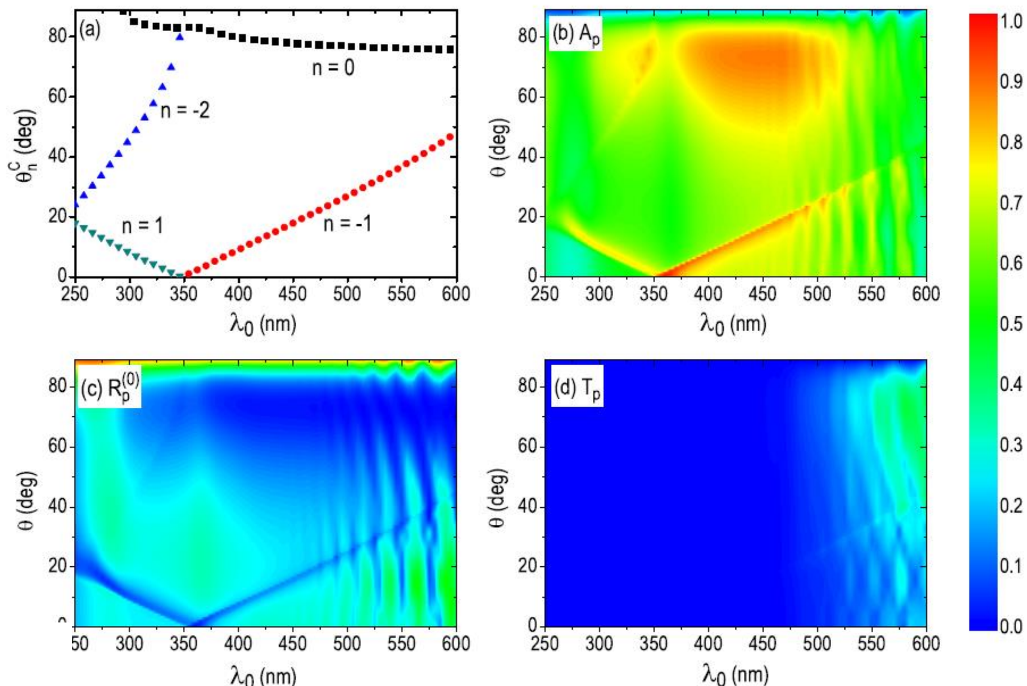


(c) Practical configuration with periodically corrugated guiding interface

$$\theta_n^{\mathrm{C}} = \sin^{-1}\left\{\frac{\mathrm{Re}(q) - 2\pi n/L}{k_0 n_d}\right\}$$

$$A_p = 1 - (R_p + T_p).$$

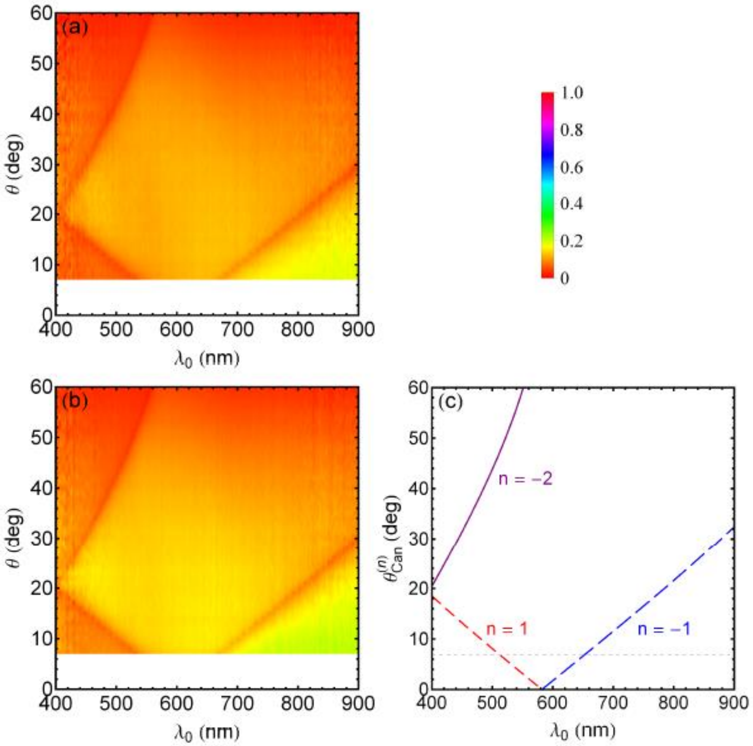
$$R_p = \sum_{n=-N_t}^{N_t} R_p^{(n)}, \qquad T_p = \sum_{n=-N_t}^{N_t} T_p^{(n)},$$

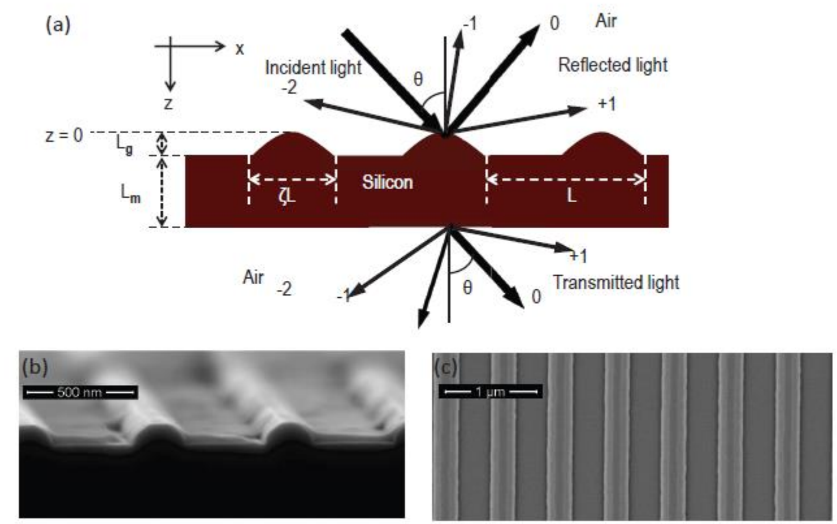


5204 OPTICS LETTERS / Vol. 39, No. 17 / September 1, 2014

Observation of the Uller–Zenneck wave

Muhammad Faryad[1,2] and Akhlesh Lakhtakia[1,*]

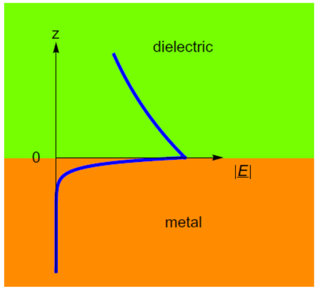




(a) Schematic, and (b,c) fabricated samples

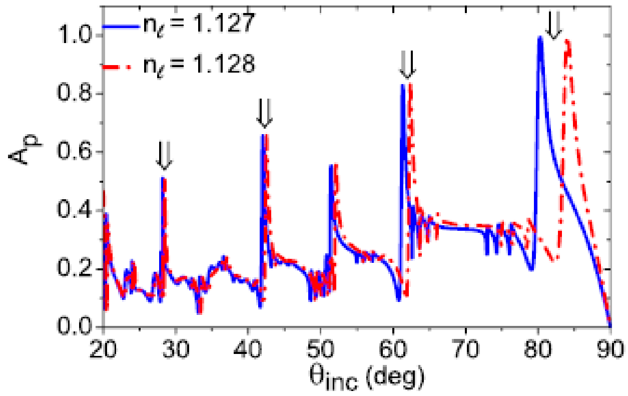
(left) Measured specular reflectance of two replicated samples
(right) Theoretical predictions from canonical problem

Optical Sensing



The basic principle of sensing with surface wave is:

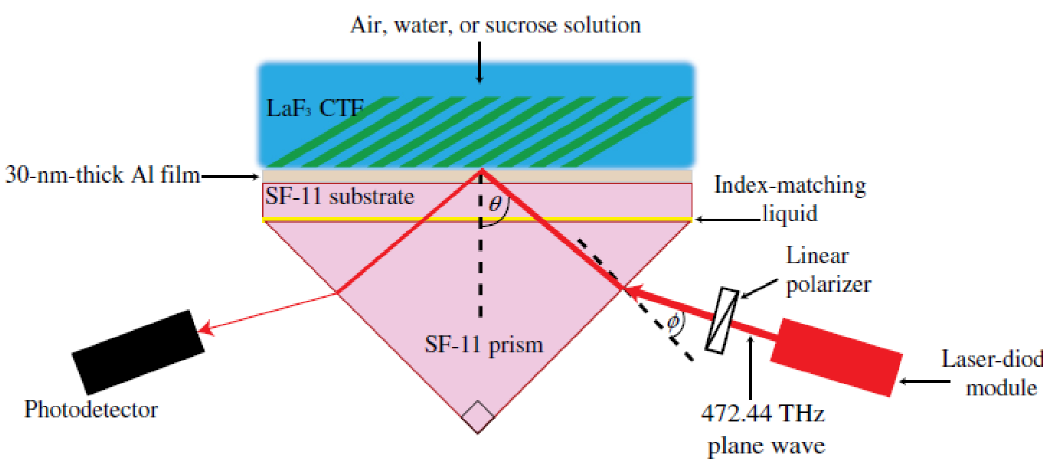
The change in the wavenumber of the surface wave due to small change in the refractive index of the partnering materials resulting in change in the excitation angle

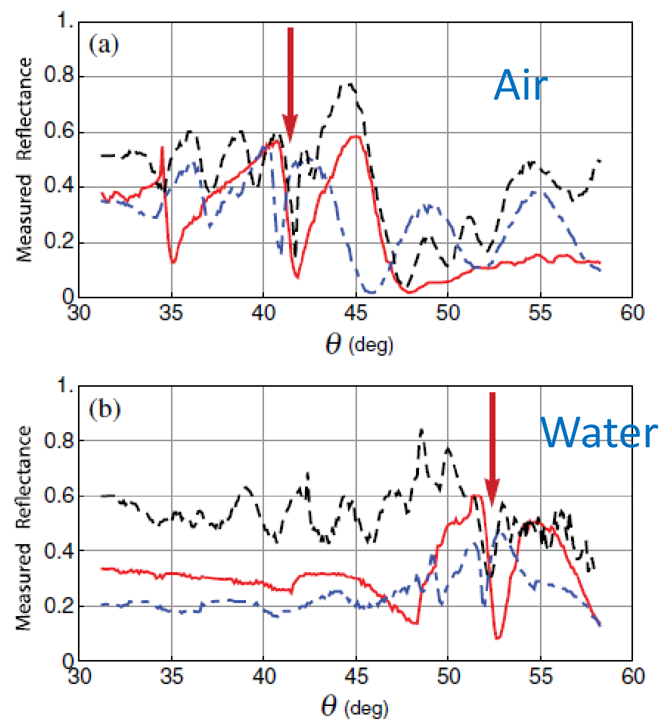


Journal of Nanophotonics 083986-1 Vol. 8, 2014

Surface plasmonic polaritonic sensor using a dielectric columnar thin film

Stephen E. Swiontek,* Muhammad Faryad, and Akhlesh Lakhtakia





Plasmonics
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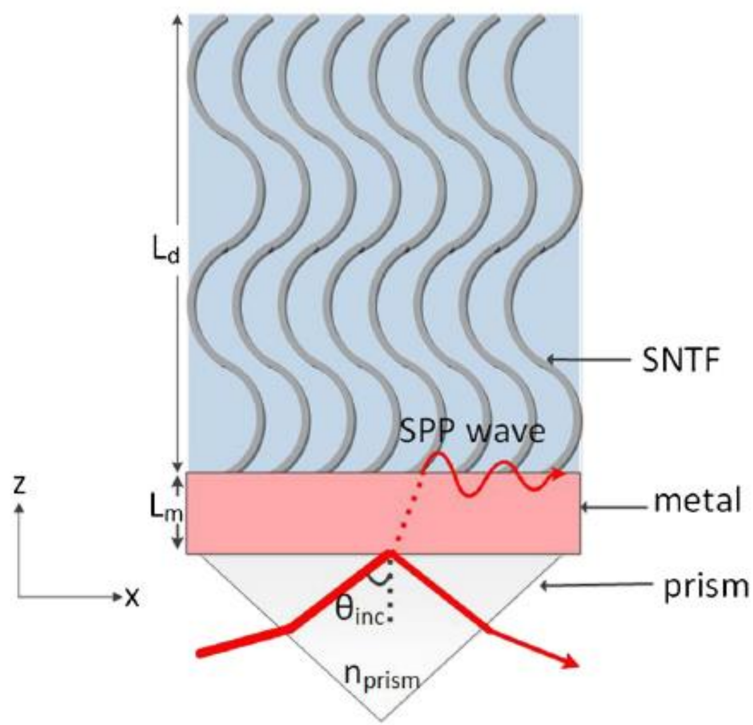
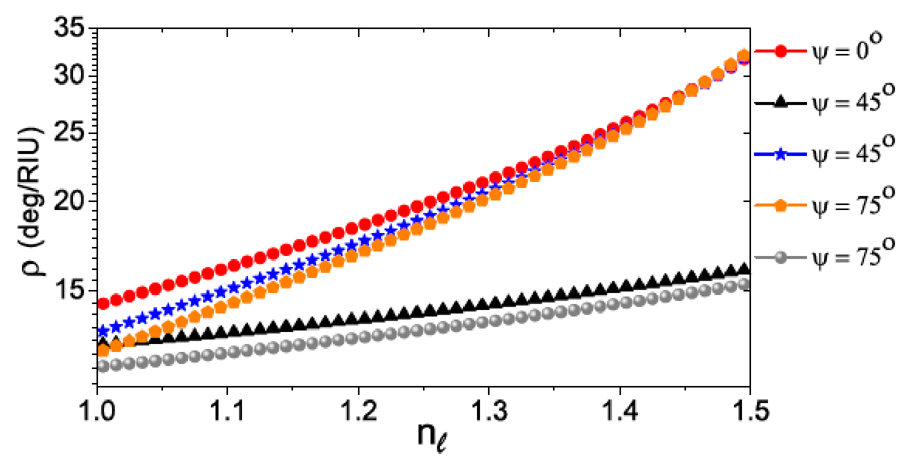
Multiplasmonic Optical Sensor Using Sculptured Nematic Thin Films

Farhat Abbas · Qaisar A. Naqvi · Muhammad Faryad



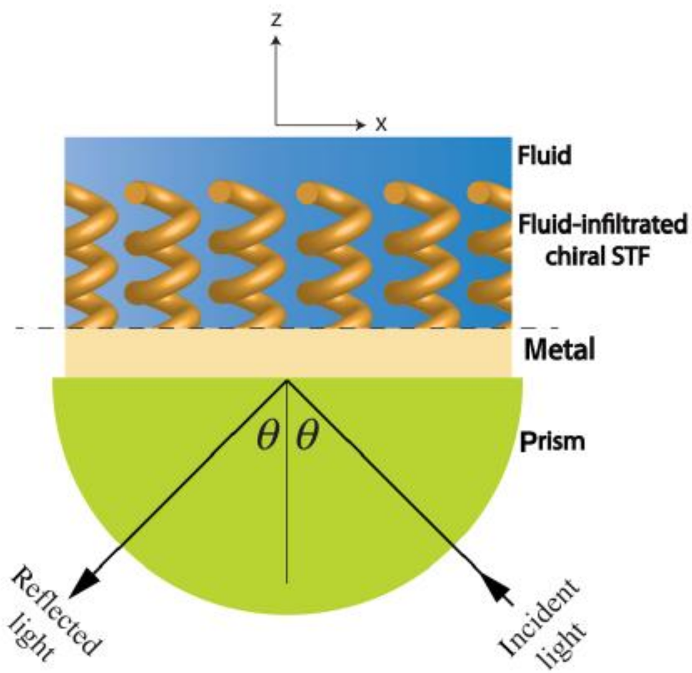
$$\rho = \frac{d\theta_{\rm inc}(n_\ell)}{dn_\ell}$$



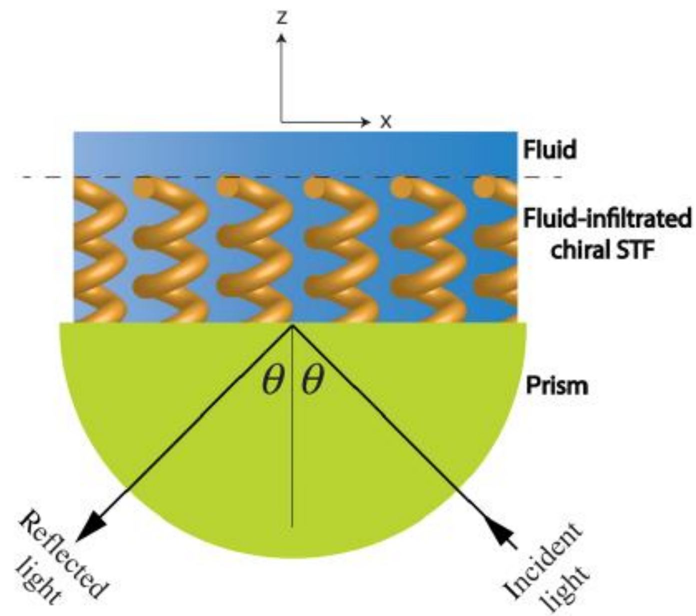
Journal of Nanophotonics 083072-9 Vol. 8, 2014

Theory of optical sensing with Dyakonov–Tamm waves

Akhlesh Lakhtakia[a,*] and Muhammad Faryad[b]



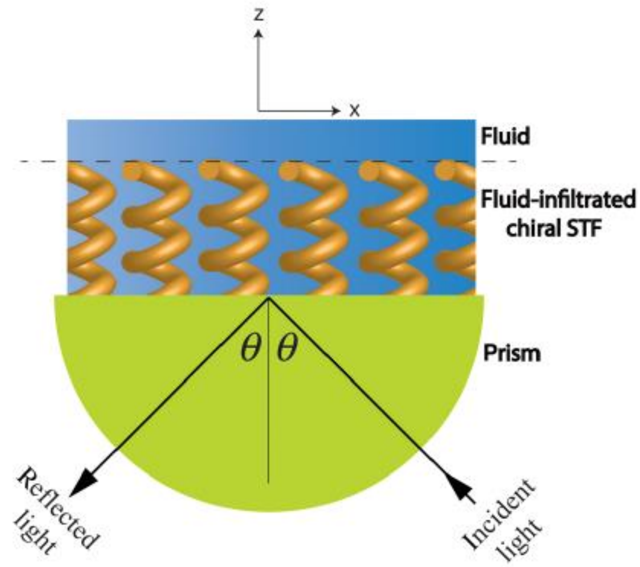
Sensing with SPP waves



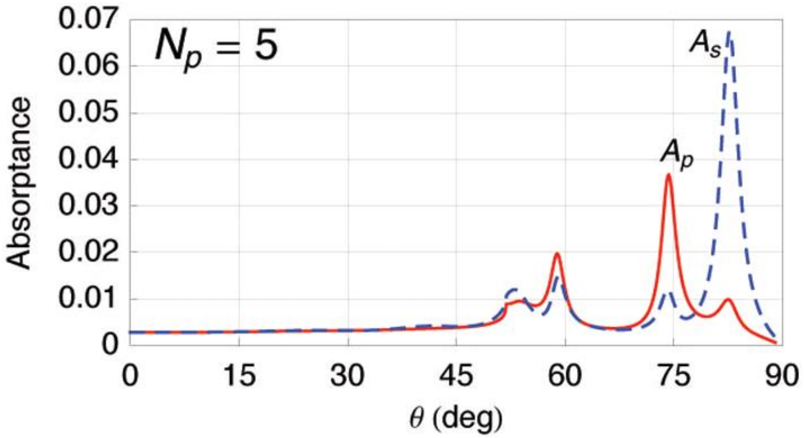
Sensing with Dyakonov--Tamm waves

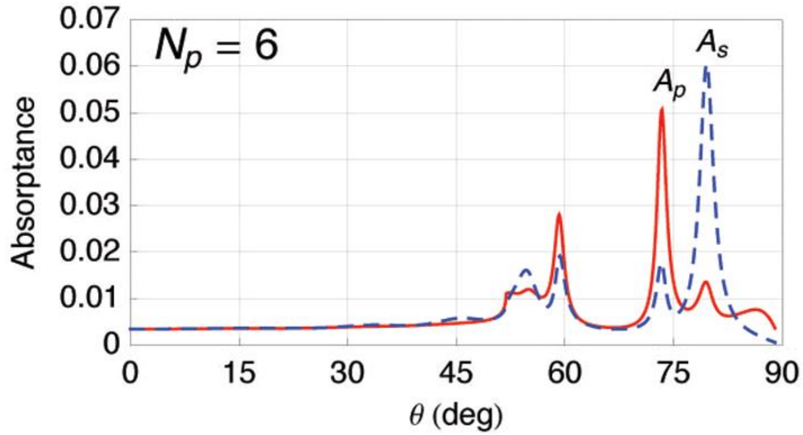
Sensing using Dyakonov—Tamm waves

Configuration 1



1. ~58 deg /RIU for n_ℓ~1.333 to ~88 deg /RIU for n_ℓ~1.5 on the higher-v_p branch of DT waves, and
2. ~82 deg /RIU for n_ℓ~1.333 to ~171 deg /RIU for n_ℓ~1.467 on the lower-v_p branch of DT waves.



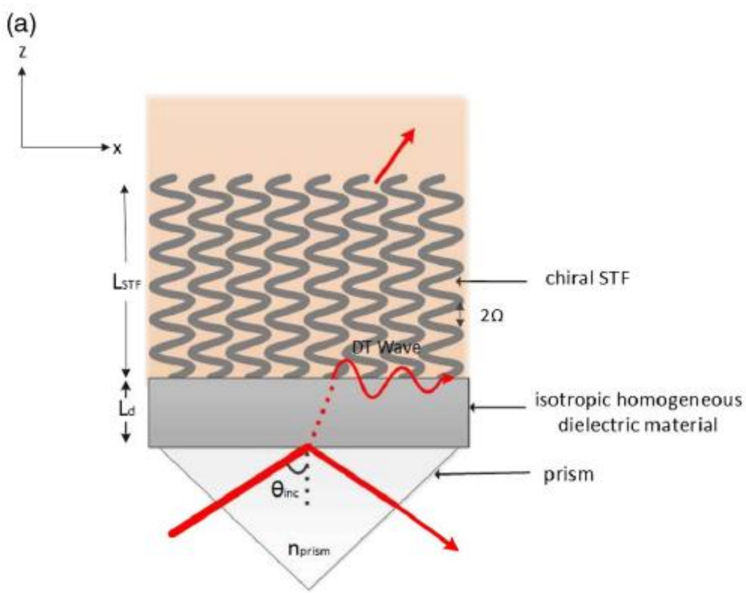


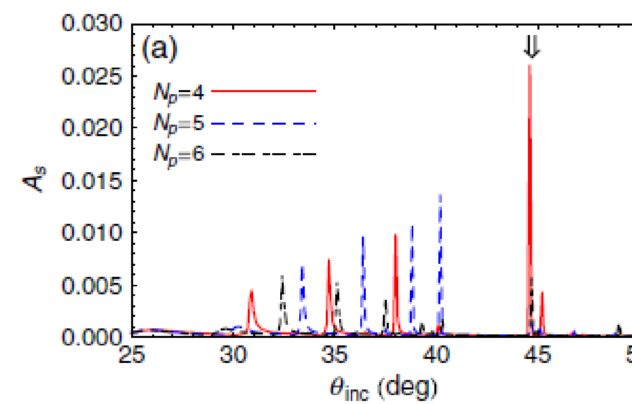
An optical-sensing modality that exploits Dyakonov–Tamm waves

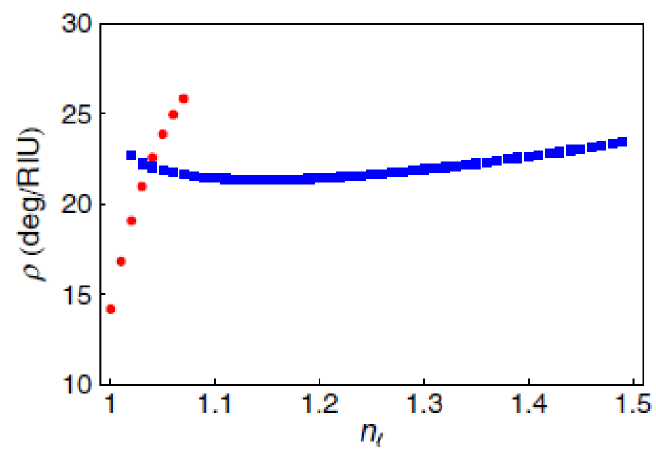
Farhat Abbas,[1] Akhlesh Lakhtakia,[2] Qaisar A. Naqvi,[1] and Muhammad Faryad[3,*]

Sensing using Dyakonov—Tamm waves

Configuration 1

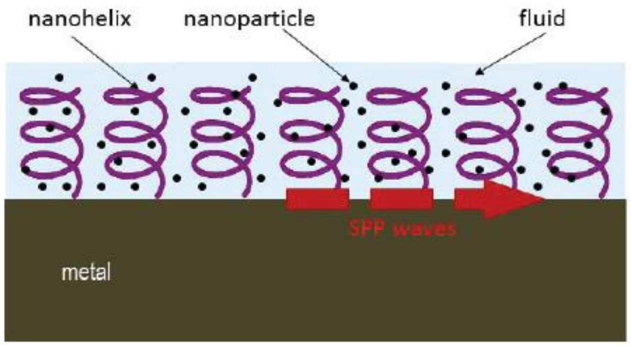




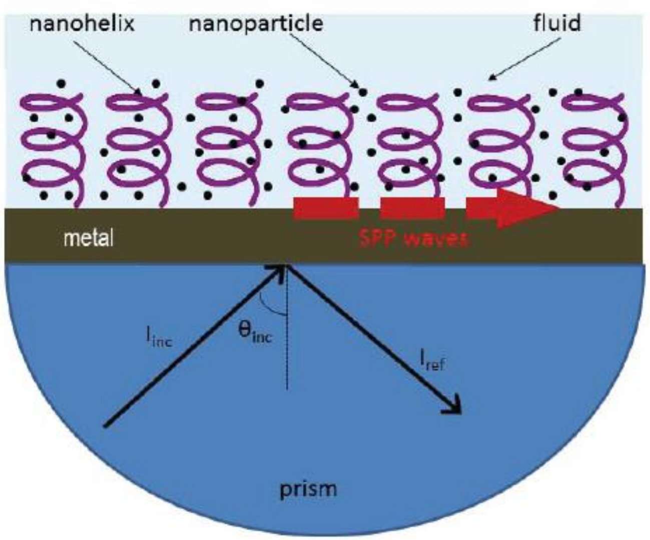


Enhancement of sensitivity of multiple surface-plasmonic-polaritonic sensor using metallic nanoparticles

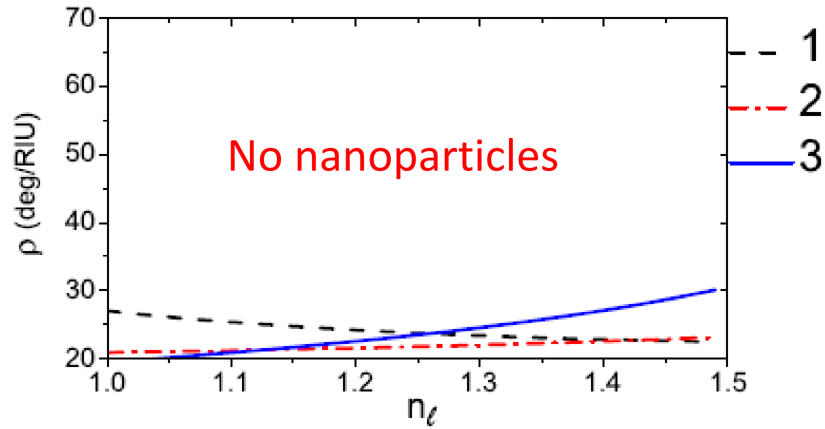
Farhat Abbas · Muhammad Faryad · Stephen E. Swiontek · Akhlesh Lakhtakia

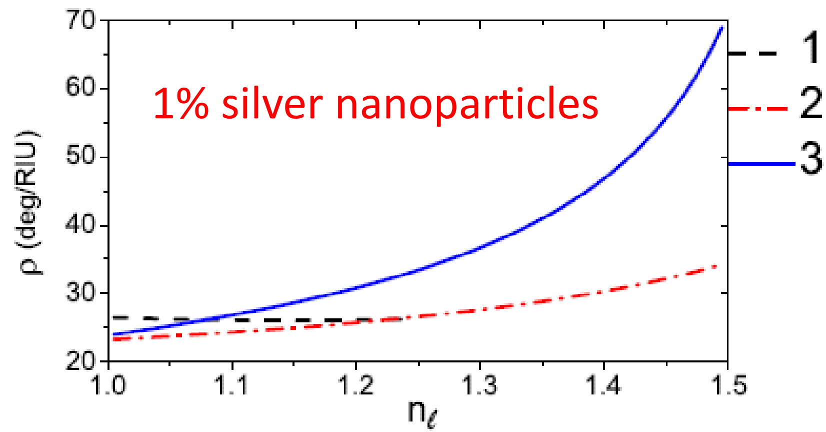


(a)



(b)





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A highly sensitive multiplasmonic sensor using hyperbolic chiral sculptured thin films

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Department of Physics, Lahore University of Management Sciences, Lahore 54792, Pakistan

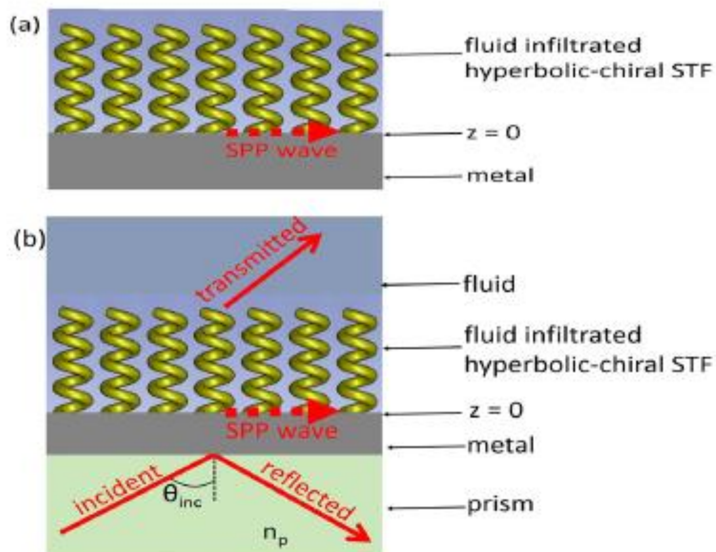


FIG. 1. **Schematic diagrams:** Schematic representations of (a) the canonical boundary-value problem and (b) the prism-coupled configuration.

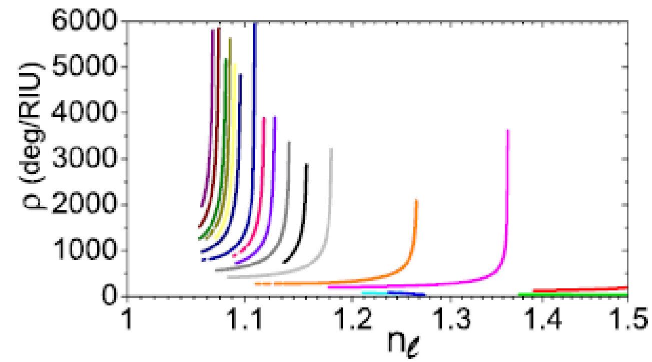
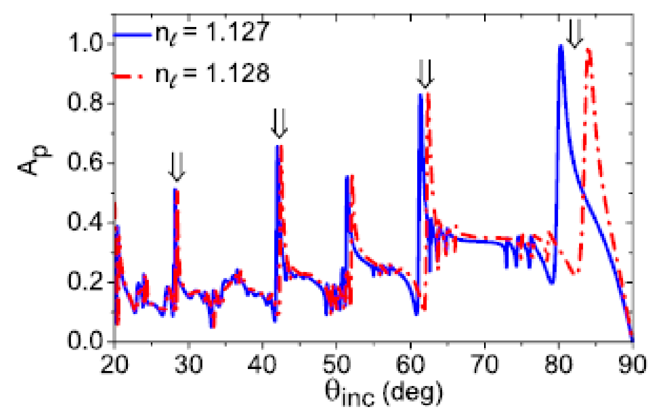


FIG. 6. **Prism-coupled configuration:** Sensitivity ρ as a function of the refractive index n_ℓ in the prism-coupled configuration computed via Eq. (8). Each branch corresponds to a branch in Fig. 2.



The sensitivity increases because of the higher field enhancement when hyperbolic medium is used

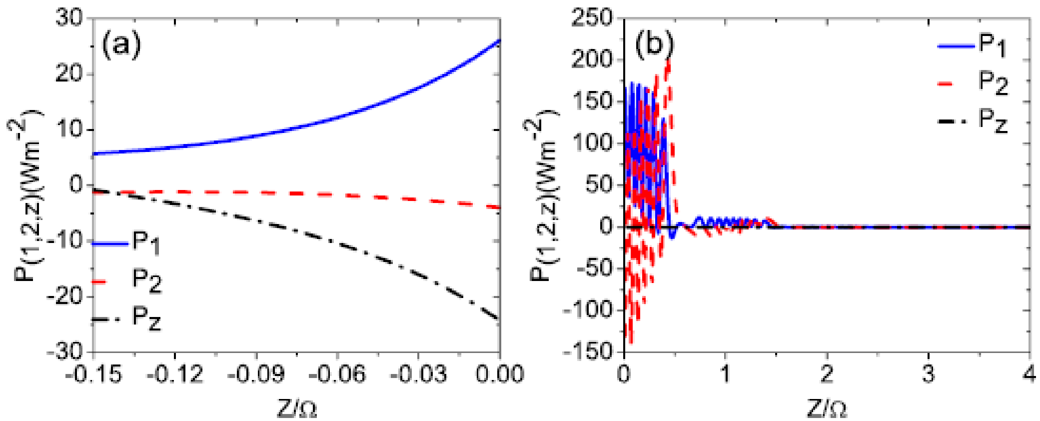


FIG. 9. **Prism-coupled configuration:** The components of the time-averaged Poynting vector as a function of z in (a) the metallic film and (b) the hyperbolic chiral STF, when $n_\ell = 1.127$, $\theta_{inc} = 42.02^\circ$, $L_{STF} = 4\Omega$, $n_p = 2.6$, and $L_m = 15$ nm in the prism-coupled configuration for the p-polarized incident plane wave with the magnitude of the electric field of the incident wave as 1 V m^{-1}. P_1 is along the direction of propagation, P_2 is perpendicular to the direction of propagation but lies in the interface plane, and P_z is perpendicular to the interface. The angle of incidence $\theta_{inc} = 42.02^\circ$ corresponds to one of the peaks in Fig. 8.

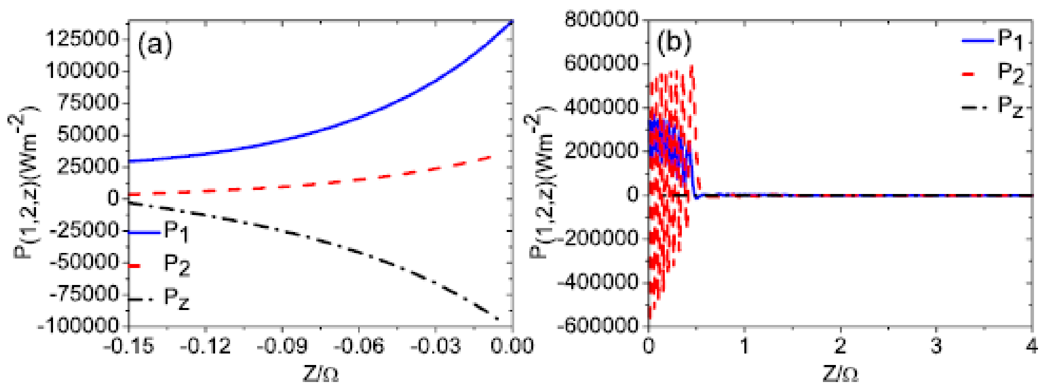


FIG. 10. **Prism-coupled configuration:** Same as Fig. 9 except for $\theta_{inc} = 61.32^\circ$.

Conclusions

- Periodically nonhomogeneous dielectric material can support a wide variety of surface electromagnetic waves
- Multiple SPP waves, Dyakonov—Tamm waves, and Tamm waves can be excited in the prism coupled configuration
- Sculptured thin films can be used to optically sense a fluid infiltrating it using surface waves to design highly sensitive and more reliable sensors

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