Radiation of surface polaritons by an annular beam coaxially enclosing a cylindrical waveguide

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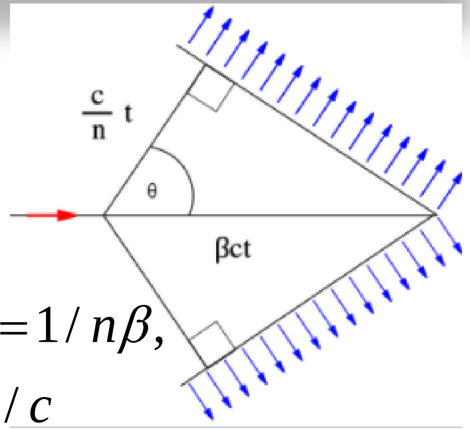
Outline

- Radiation processes in media
- Surface plasmon polaritons
    - Annular beam around a cylinder
- Conclusions

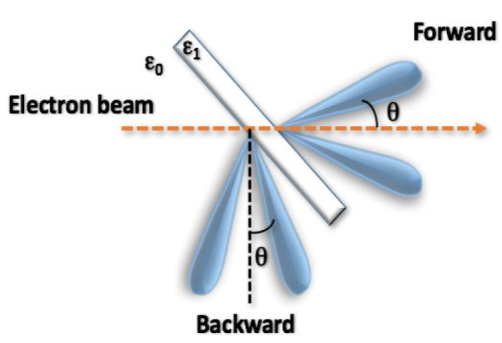
Radiation processes in media

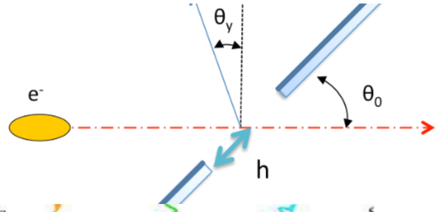
Interaction of charged particles with media gives rise to various types of radiation processes

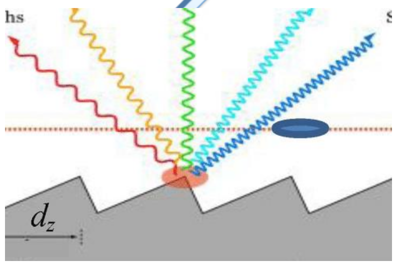
- Cherenkov radiation: charged particles passing through optically transparent media at speeds greater than the speed of light in that medium
- Transition radiation: charged particles pass the boundary between two media with different refractive index
- Diffraction radiation: charged particle moves in the vicinity of a dielectric medium
- Smith-Purcell radiation/Resonance diffraction radiation
  Diffraction radiation on periodic structures



$$\cos\theta = 1/n\beta,$$
$$\beta = v/c$$





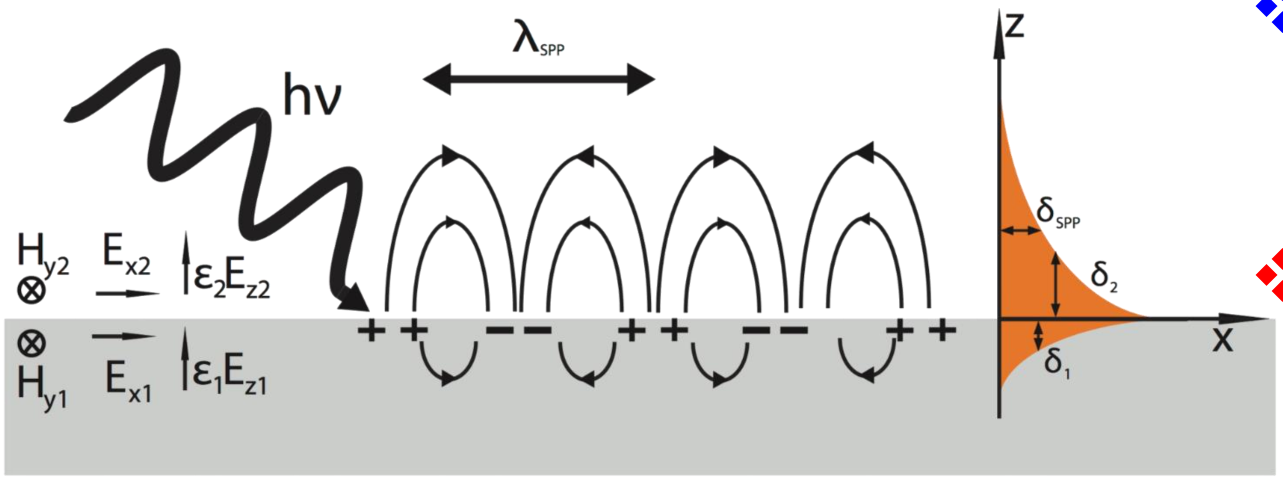


Surface Plasmon Polaritons

- Interfaces between two media with different electromagnetic characteristics give arise to new types of electromagnetic modes → Surface modes
- Surface modes depend on the geometry of the separating boundary and carry an important information on the electromagnetic properties of the contacting media
- Among the various types of surface waves, the surface plasmon polaritons (SPP) have been a powerful tool in the wide range of investigations including
  - Surface imaging
  - Surface-enhanced Raman spectroscopy
  - Data storage and Biosensors
  - Plasmonic waveguides
  - Light-emitting devices
  - Plasmonic solar cells, etc.

Surface Plasmon Polaritons

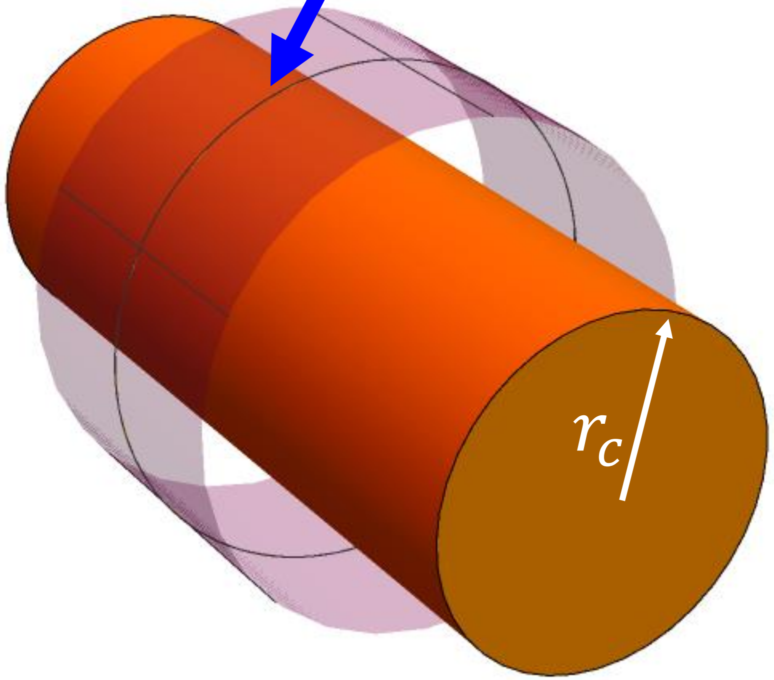
- SPPs are evanescent electromagnetic waves propagating along a metal-dielectric interface as a result of collective oscillations of electron subsystem coupled to electromagnetic field
- SPPs exist in frequency ranges where the real part of the permittivity undergoes a change of the sign at the interface
- Perpendicular to the interface SPPs have subwavelength-scale confinement



- Remarkable properties of SPPs include
  - Possibility of concentrating electromagnetic fields beyond the diffraction limit of light waves
  - Enhancing the local field strengths by orders of magnitude

Problem setup

$$j_l(x) = \delta_{3l} \frac{qv}{r} \delta(r - r_0) \delta(z - vt)$$



- Cylindrical waveguide with permittivity ε_0 immersed into a homogeneous medium with permittivity ε_1
- An annular beam coaxially moves outside the cylinder
- The radiation from annular beams of arbitrary distribution (negligible overlaps with the dielectric cylinder) can also be obtained (by means of integration)

Charge density: $\rho(x) = q\delta(r - r_0)\delta(z - vt) / r$

Total charge of the beam: $Q = 2\pi q$

Green's tensor

The components of the Green's tensor

$$G_{l3}(r,r_0) = G_{l3}^{(0)}(r,r_0) + i^{2-l}\sum_p p^{l-1}\overline{C}_n^{(3p)}(r_c,r_0)H_{n+p}(\lambda_1 r),$$

$$G_{33}(r,r_0) = G_{33}^{(0)}(r,r_0) - \frac{\pi}{2i}H_n(\lambda_1 r_0)\frac{V_n^J}{V_n^H}H_n(\lambda_1 r),$$

$$\overline{C}_n^{(3p)}(r_c,r') = k_z\frac{J_n(\lambda_0 r_c)}{2\alpha_n}\frac{H_n(\lambda_1 r')}{V_n^H}\frac{J_{n+p}(\lambda_0 r_c)}{r_c V_{n+p}^H}$$

$$V_n^F = \lambda_1 J_n(\lambda_0 r_c)F_n'(\lambda_1 r_c) - \lambda_0 F_n(\lambda_1 r_c)J_n'(\lambda_0 r_c).$$

$$\lambda_j^2 = k_z^2\left(\beta^2\varepsilon_j - 1\right), \quad j = 0, 1,$$

$$\alpha_n = \frac{\varepsilon_0}{\varepsilon_1 - \varepsilon_0} - \frac{\lambda_0}{2}J_n(\lambda_0 r_1)\sum_{l=\pm 1} l\frac{H_{n+l}(\lambda_1 r_1)}{V_{n+l}^H}.$$

$\alpha_n = 0$: eigenmodes of the dielectric cylinder

The Vector and Scalar Potentials

$$A_i(x) = -\frac{1}{2\pi^2 c}\int d^4x' \sum_{l=1}^{3} G_{il}(x,x')j_l(x')$$

$$\begin{aligned} A_1(k_z,r) &= \frac{2qv}{ic} D H_0(\lambda_1 r_0) H_1(\lambda_1 r), \\ A_3(k_z,r) &= \frac{i\pi qv}{c}\left[J_0(\lambda_1 r_<)H_0(\lambda_1 r_>) - \frac{V_0^J}{V_0^H} H_0(\lambda_1 r_0) H_0(\lambda_1 r)\right], \end{aligned}$$

for $r > r_c$

$$\begin{aligned} A_1(k_z,r) &= \frac{2qv}{ic} D H_0(\lambda_1 r_0) J_1(\lambda_0 r), \\ A_3(k_z,r) &= -\frac{2qv}{c}\frac{H_0(\lambda_1 r_0)}{r_c V_0^H} J_0(\lambda_0 r), \end{aligned}$$

for $r < r_c$

Where

$$D = \frac{k_z J_0(\lambda_0 r_c)}{r_c \alpha_0(\omega,k_z) V_0^H V_1^H}\begin{cases} H_1(\lambda_1 r_c), & r < r_c \\ J_1(\lambda_0 r_c), & r > r_c \end{cases}$$

$$\varphi(k_z,r) = -\frac{2qv}{\omega\varepsilon_0}\left(\lambda_0 D + \frac{k_z}{r_c V_0^H}\right) H_0(\lambda_1 r_0) J_0(\lambda_0 r) = -\frac{2q}{\varepsilon_0}\left(\sqrt{\beta^2\varepsilon_0 - 1} D + \frac{1}{r_c V_0^H}\right) H_0(\lambda_1 r_0) J_0(\lambda_0 r).$$

for $r < r_c$

$$\varphi(k_z,r) = -\frac{\pi q}{i\varepsilon_1}\left[J_0(\lambda_1 r_<)H_0(\lambda_1 r_>) + \left(\frac{2i}{\pi}\sqrt{\beta^2\varepsilon_1 - 1} D - \frac{V_0^J}{V_0^H}\right) H_0(\lambda_1 r_0) H_0(\lambda_1 r)\right].$$

for $r > r_c$

Radiation of Surface Polaritons

For surface polaritons the real parts of the permittivies ε_0 and ε_1 should have opposite signs.

$\varepsilon_0' < 0 < \varepsilon_1'$ and $\beta^2\varepsilon_1' < 1$

$$\gamma_j = \sqrt{1 - \beta^2\varepsilon_j}.$$

$$\lambda_j r_c = i\gamma_j u,\ u = k_z r_c = \omega r_c / v.$$

Drude model

$$\varepsilon_0(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega},$$

The dispersion for the permittivity ε_1 is weak in the spectral range under consideration

Modified Bessel functions

$$\begin{aligned} J_0(\lambda_0 r_c) &= I_0(\gamma_0 u),\ J_1(\lambda_0 r_c) = iI_1(\gamma_0 u), \\ H_0(\lambda_1 r_c) &= \frac{2}{\pi i}K_0(\gamma_1 u),\ H_1(\lambda_1 r_c) = -\frac{2}{\pi}K_1(\gamma_1 u) \end{aligned}$$

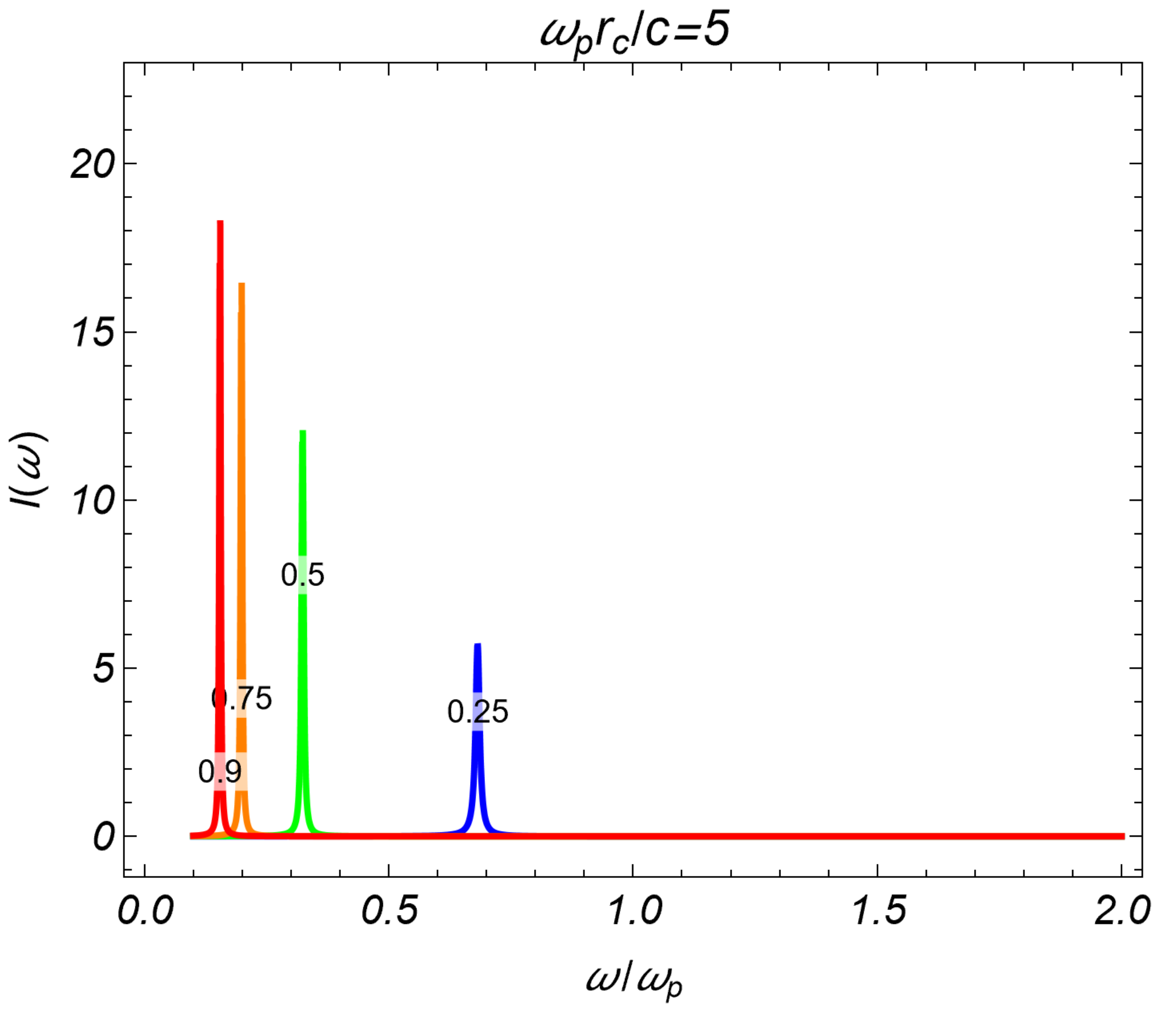
The dimensionless quantity associated with the energy loss spectral density

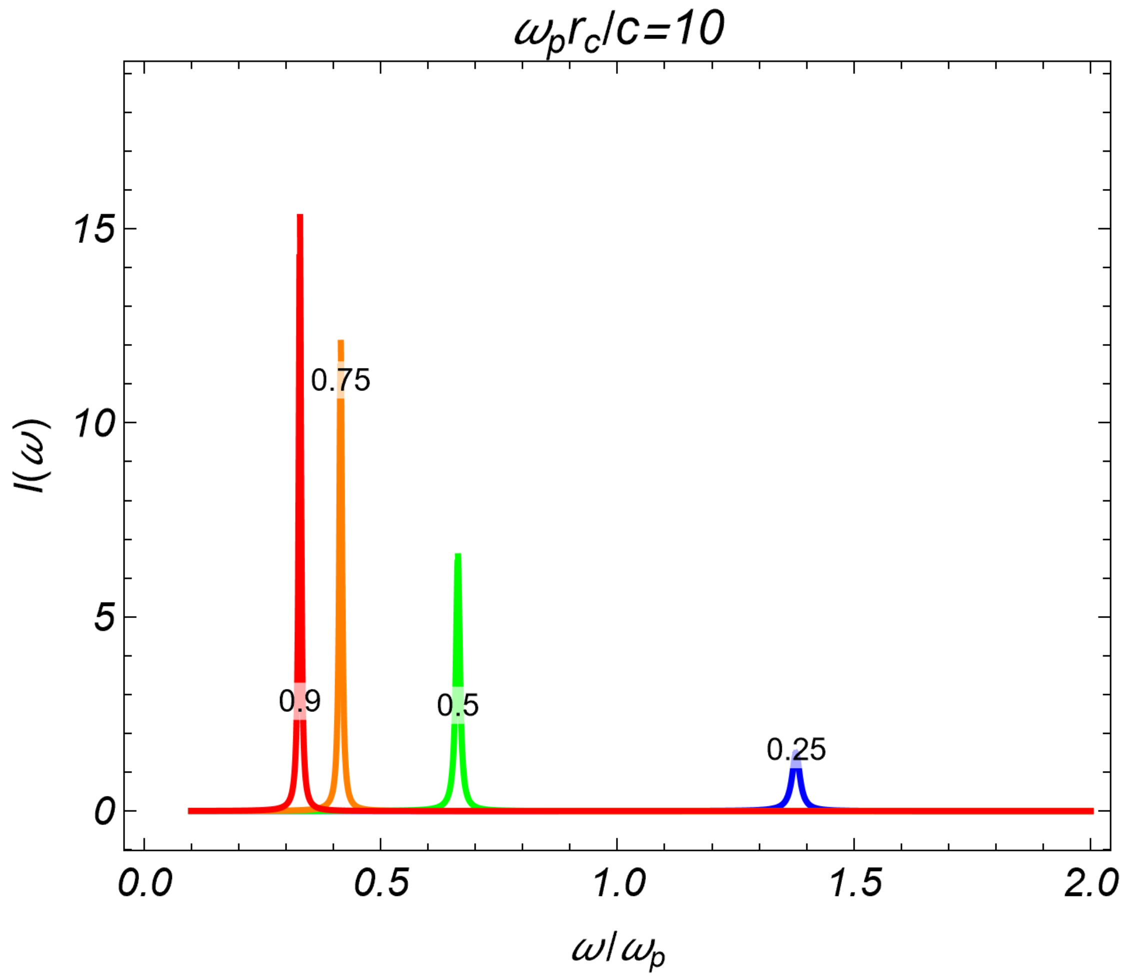
$$I(\omega) = \frac{r_c}{Q^2}\frac{d\mathcal{E}}{d\omega},$$

$$I(\omega) = \frac{2vr_c\omega}{\pi c^2}\mathrm{Re}\left[i\left(1 - \frac{1}{\beta^2\varepsilon_1}\right)\frac{\varepsilon_0\gamma_1 I_1(\gamma_0 u)I_0(\gamma_1 u) - \varepsilon_1\gamma_0 I_0(\gamma_0 u)I_1(\gamma_1 u)}{\varepsilon_1\gamma_0 I_0(\gamma_0 u)K_1(\gamma_1 u) + \varepsilon_0\gamma_1 I_1(\gamma_0 u)K_0(\gamma_1 u)}K_0^2(\gamma_1 u r_0/r_c)\right]$$

Numerical results

r/r_c=1.05





Conclusions

- We have considered an annular beam coaxially moving outside a cylindrical waveguide.
- A change of the sign in the dielectric permittivity ε leads to the generation of surface plasmon-polaritons localised on the boundary of two media.
- Sharp peaks in the surface plasmon-polariton intensity appear.
- The characteristics of the peaks can be controlled by the choice of the velocity of the annular beam and the plasma frequency.

Thank you for your attention!