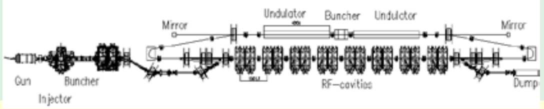

Terahertz surface plasmons on real metal-dielectric structures: comparison of theory and experiments

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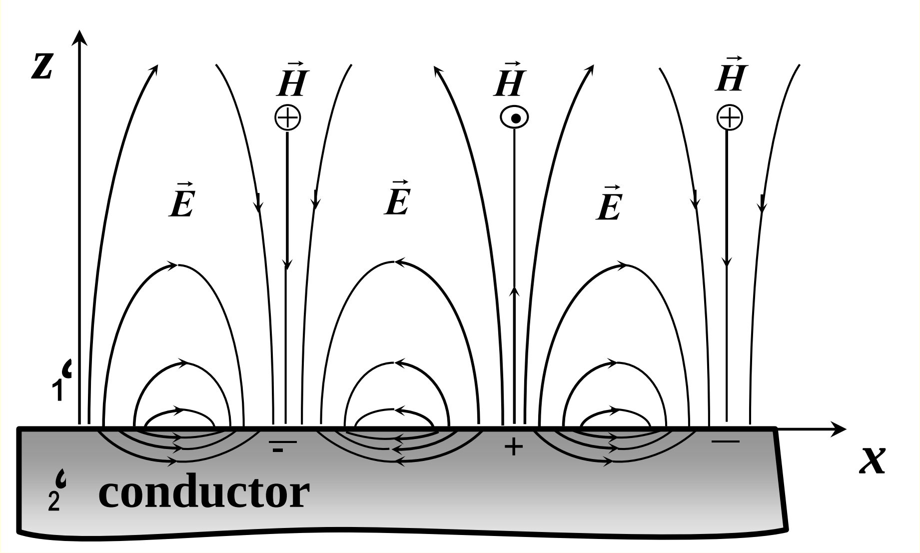
SFR - 2016

Surface plasmons (SPs)

Surface plasmons (SPs) are electromagnetic excitations propagating at the interface between a dielectric and a conductor, evanescently confined in the perpendicular direction, and related with oscillations of the conductor's electron plasma. Stefan A. Maier, *Plasmonics: Fundamentals and Applications,* 2007

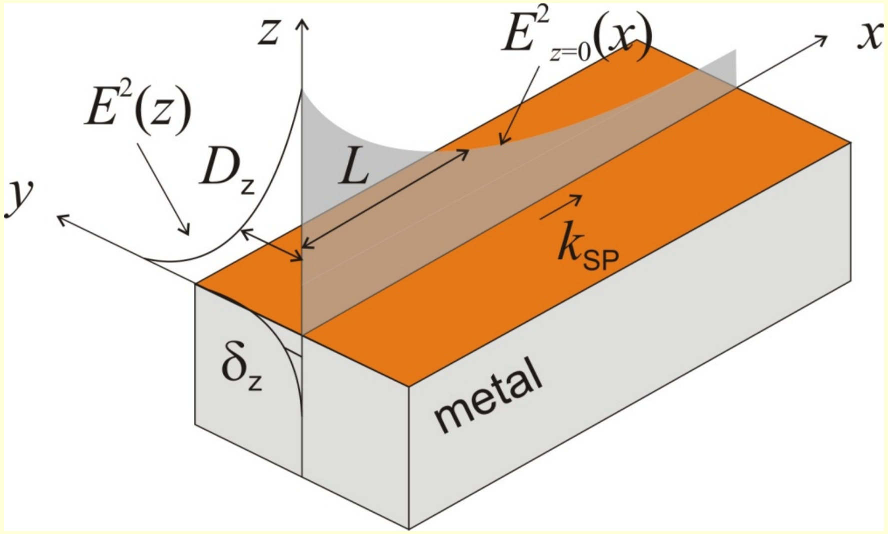


$$\mathbf{E} = \mathbf{E}_0 \exp\left(\mp\kappa_{1,2} z\right)\exp\left(ik_{\mathrm{SP}}x - i\omega t\right),$$

$$\mathbf{E}_0 = \{E_{0x}, 0, E_{0z}\},$$

$$\mathbf{B}_0 = \{0, B_{0y}, 0\}.$$

Main characteristics of surface plasmons



$L = \{2\,\mathrm{Im}(k_s)\}^{-1}$ – propagation length

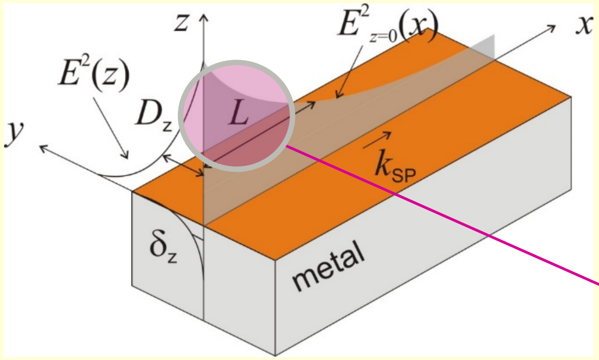
$D_z = \{2\,\mathrm{Re}(\kappa)\}^{-1}$ – decay length of SP intensity field into a dielectric

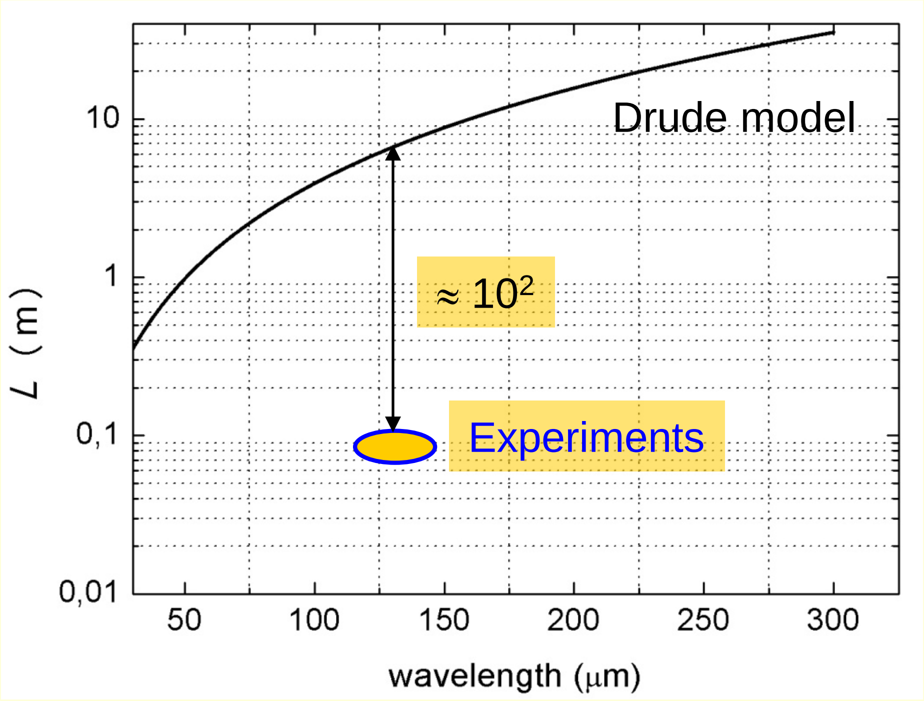
Surface plasmons in Visible and Infrared regions

- Very sensitive plasmon spectrometers (SERS): study very thin dielectric layers (monolayers), including biological substances
- Biosensors
- Information processing and transfer
- Plasmon detectors
- And so on…

In Terahertz region SPs have the same wide potential application, but they are studied insufficiently…

SP propagation length on plane surfaces in THz region: theory and experiments



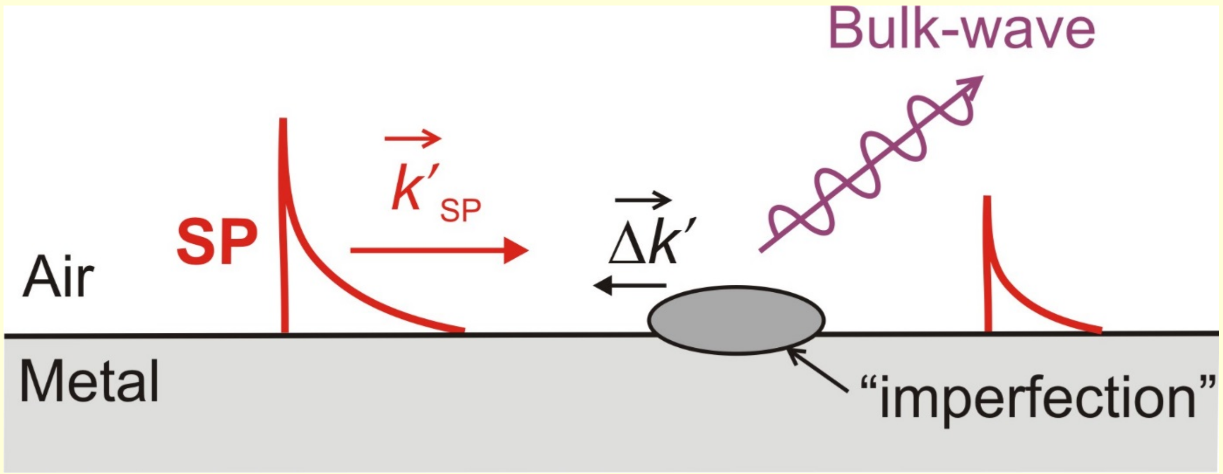


There are two main assumptions for the discrepancy:

(1) High Joule losses in a metal due to the possible difference in optical properties of the real metal surface from those of the bulk metal;

(2) “Radiative losses“ of SPs on surface imperfections

“Radiative” losses of SPs



$k_{SP} = k'_{SP} + i \cdot k''_{SP}$ - SP wave vector

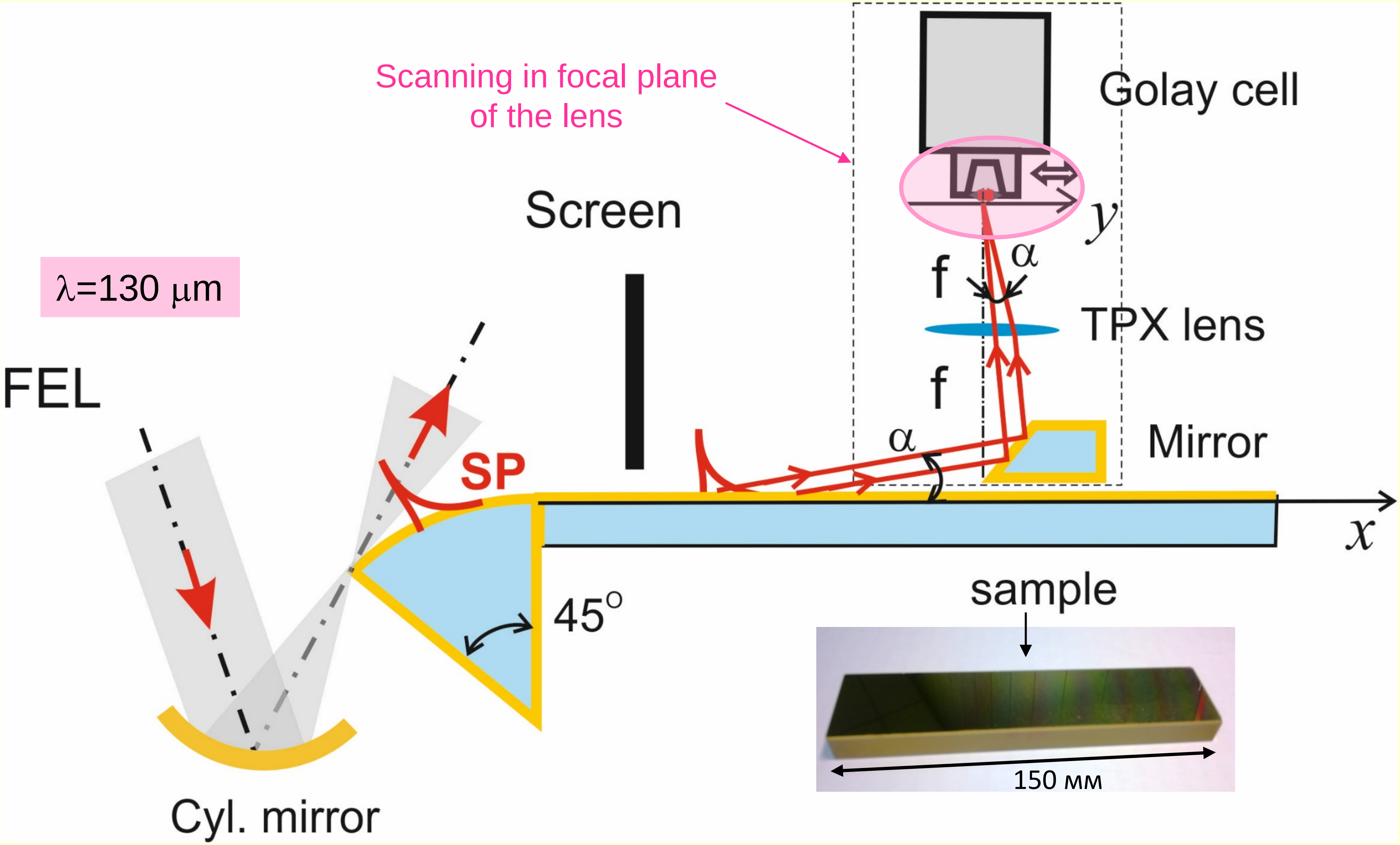
$\Delta k = \Delta k' + i \cdot \Delta k''$ - imperfection increment

$k_{Air} = n_{Air} \cdot \omega / c$ - wave vector of free wave in air

SP convert to a bulk-wave if: $\boxed{k'_{SP} - \Delta k' < k_{Air}}$

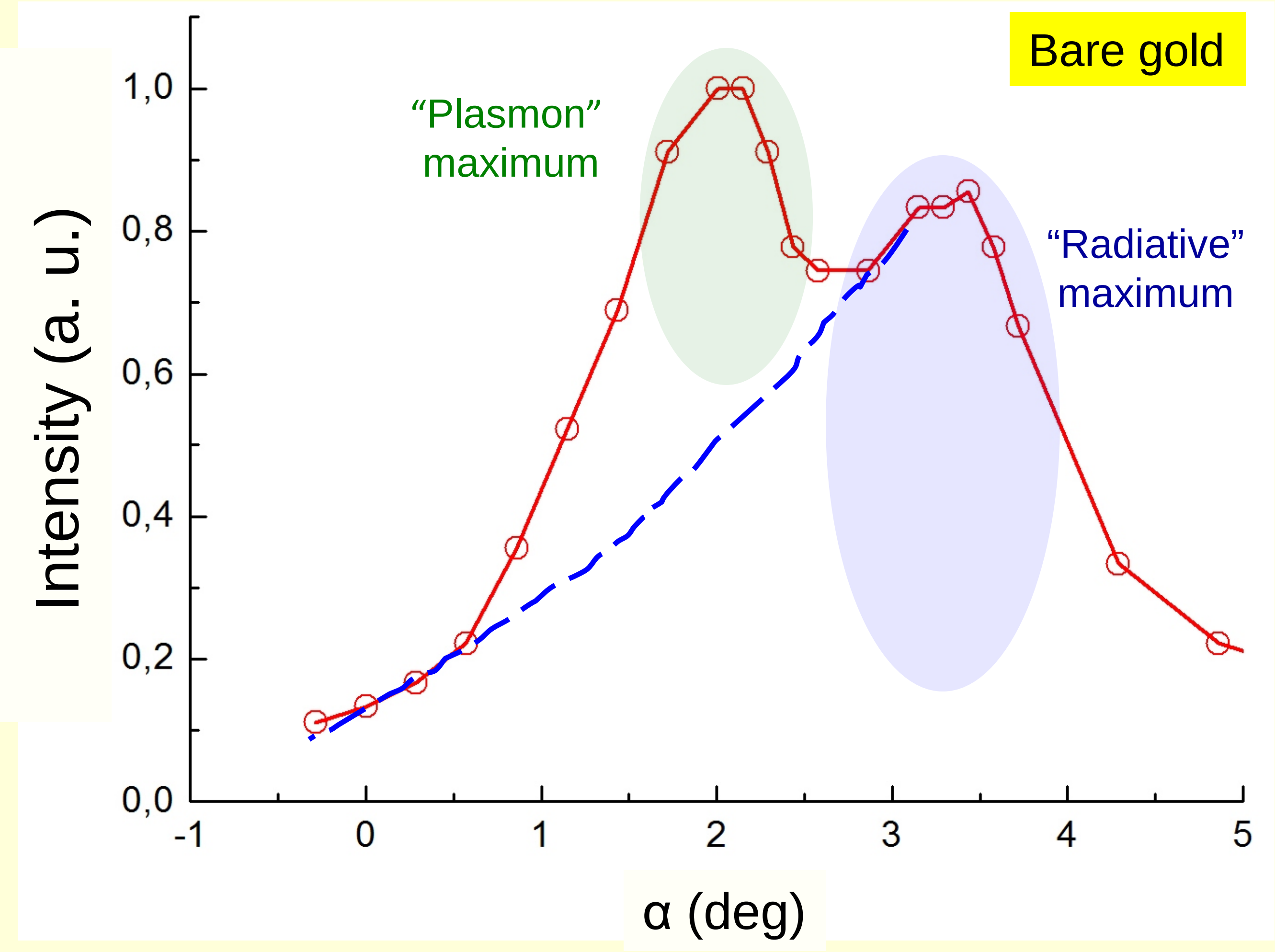
$\boxed{k'_{SP} - k_{Air} \approx 10^{-7} \cdot k_{Air}}$ $\Rightarrow$ Radiative losses must be high!

Direct measurement of "radiative" losses



Gerasimov V. V., Knyazev B. A., Nikitin A. K., et al // IRMMW-THz-2015, 23-28 Aug., Hong Kong. P. 1-2.

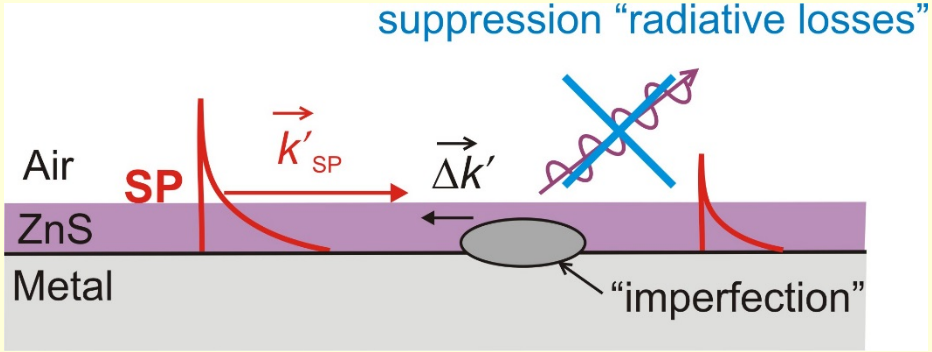
Angular pattern of incoming radiation



(1) "Radiative" losses of THz surface plasmons are very high, significantly reducing the propagation length

(2) "Radiative" losses have a wide angular spectrum

How to reduce the "radiative" losses?



SP wave vector rises when metal have a dielectric coating

$$k'_{SP}(\text{metal+dielectric}) > k'_{SP}(\text{metal})$$

If: $$k'_{SP}(\text{metal+dielectric}) - \Delta k' > k_0,$$

SPs will not be radiated into bulk waves!

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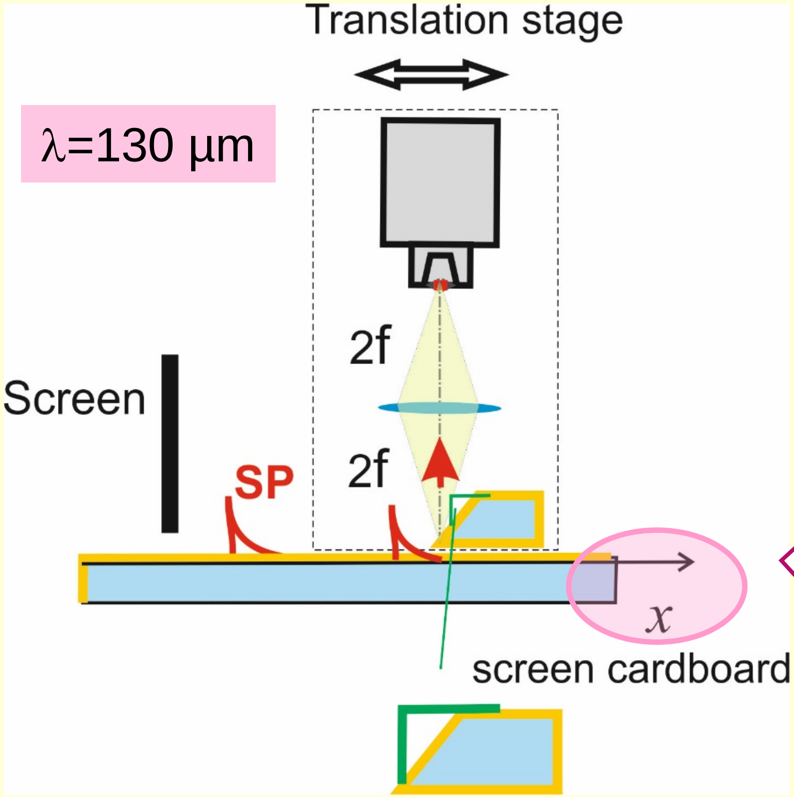
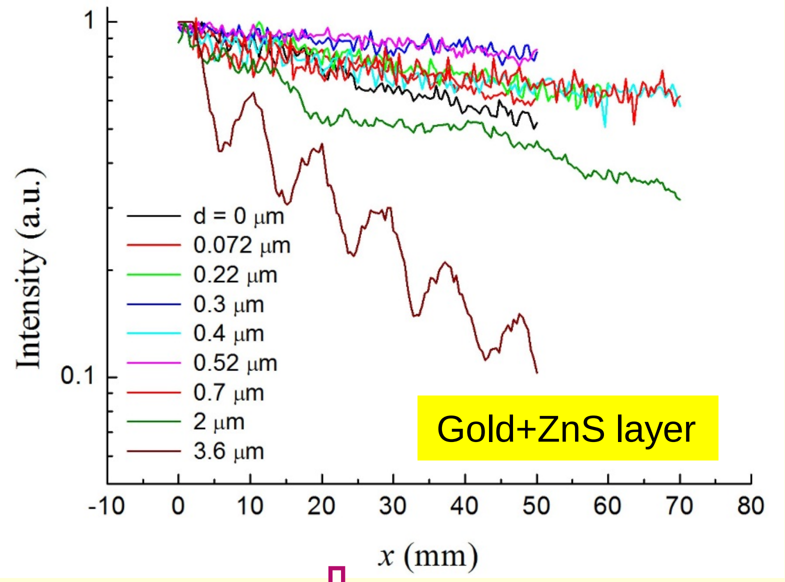
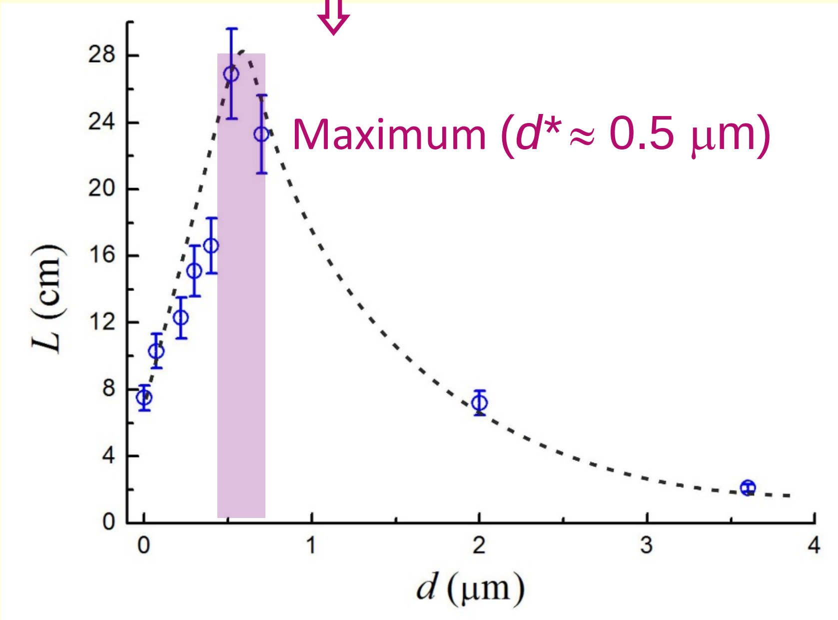
(1) Reducing "radiative" losses

(2) Increasing SP propagation length

SP propagation length vs. dielectric thickness: experiment on NovoFEL







ZnS **layer d/λ≈1/250 thick four times increased the propagation length!**

⇩

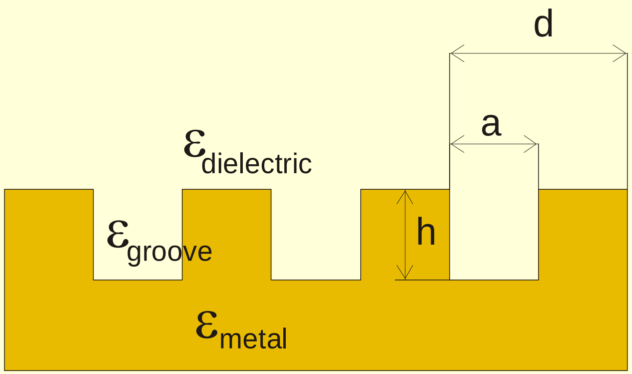
Due to significant reducing "radiative" losses…

Possible applications

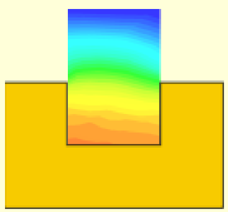
- Terahertz waveguide lines
- Integrated circuits
- Study of a large aria of metal surfaces

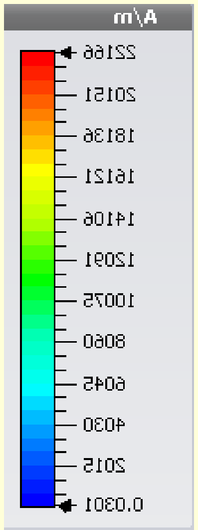
SPs on corrugated metal structures

Spoof surface plasmons (or a “mimic” plasmons)



The field distribution in the grooves (simulation in CST)



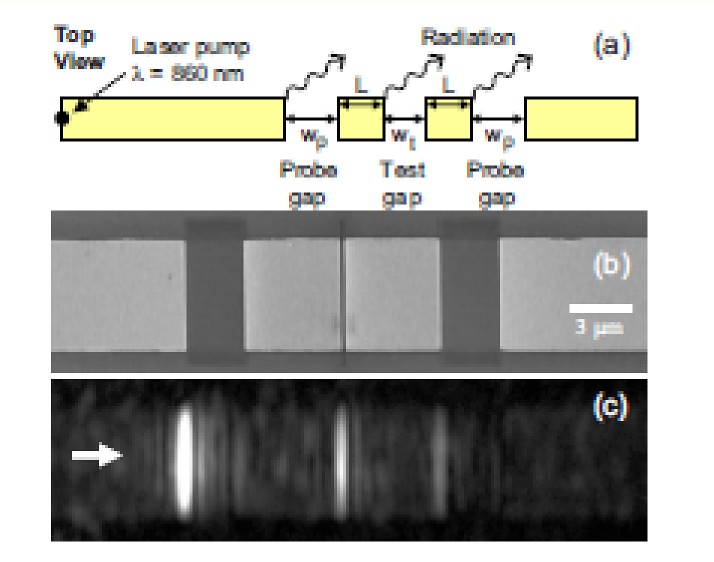


Theoretical analysis:

Optimal parameters of the groove width and depth of the corrugated surface were found for polar (biological) and non-polar liquids sensing

“V. V. Bulgakova, V. V. Gerasimov, Analytical study of terahertz spoof surface plasmons on corrugated metal-dielectric structures (poster - 056)”

Study of surface plasmon transmission through air gaps

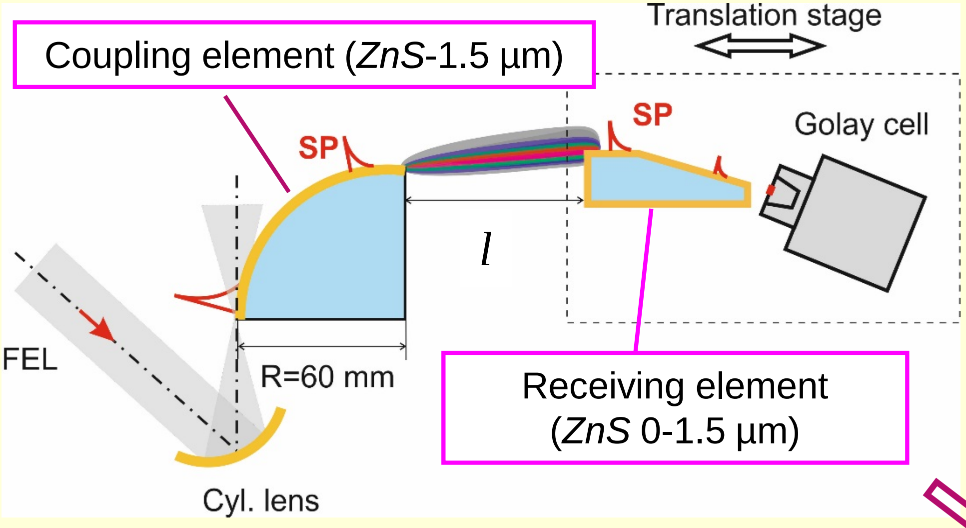


In visible range SPs can transmit several microns

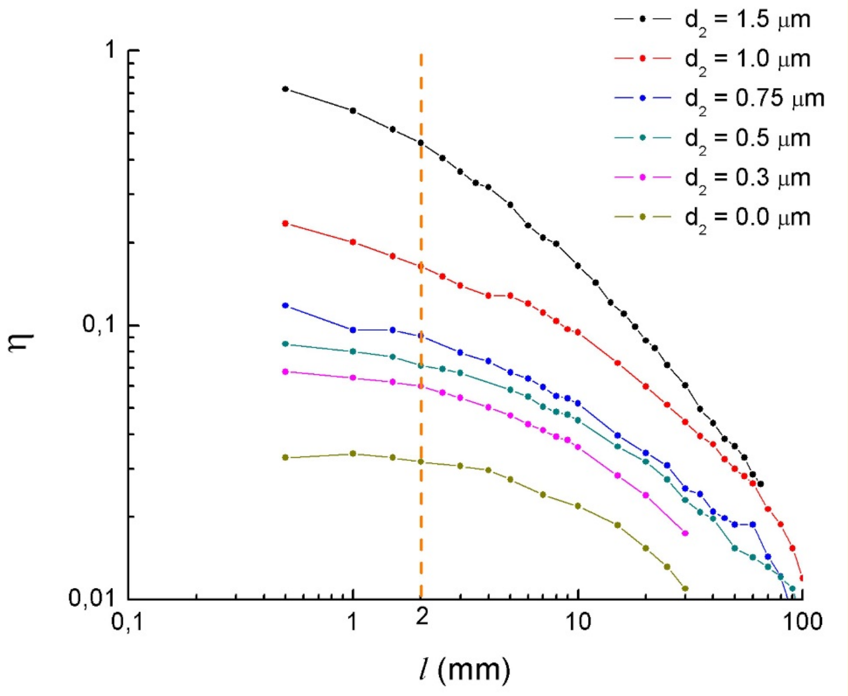
R. A. Flynn, et al // Appl. Phys. Lett. **96**, 111101 (2010).

In terahertz region the gaps must be more higher, but it didn’t study experimentally!

Experiments using THz NovoFEL radiation



Transmission efficiency

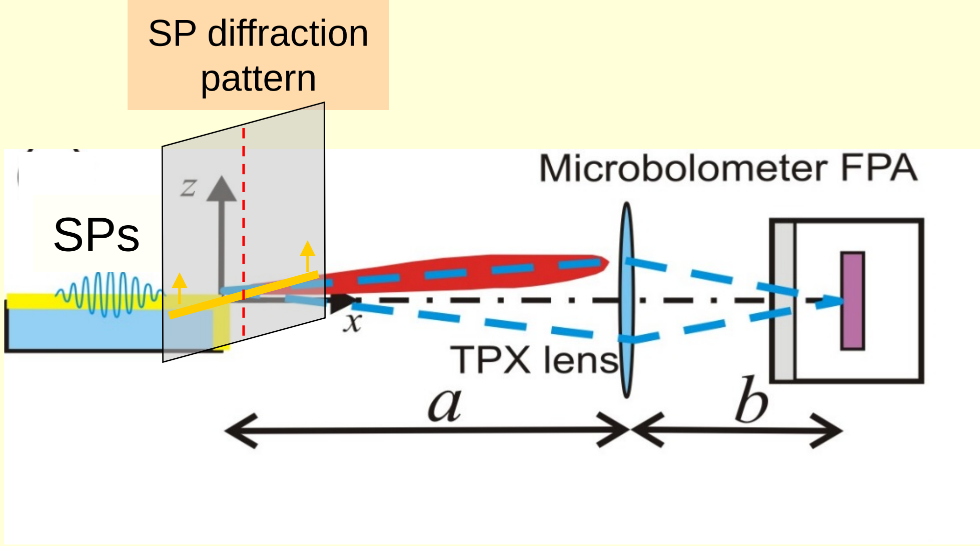


(1) THz surface plasmons can transmit 10 cm air gaps!

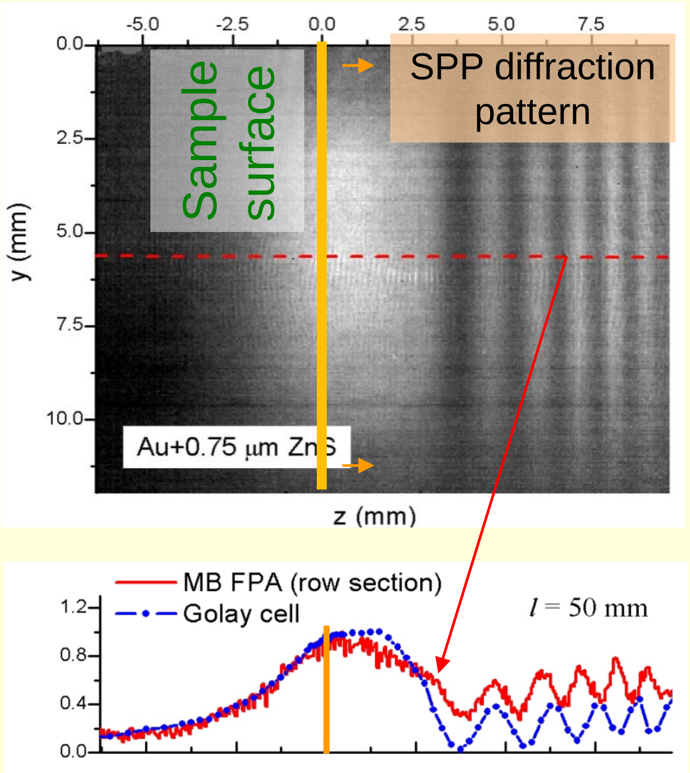
(2) Transmission efficiency depend on coupling end receiving element structures

Gerasimov V. V., Knyazev B. A., Nikitin A. K., et al
// Opt. Express 2015, V. 23(26), P. 33448-33459.

Why the SP transmission is very high?



V. V. Gerasimov, B. A. Knyazev, I. A. Kotelnikov et al
// *J. Opt. Soc. Am. B*, vol. 30, pp. 2182-2190, 2013.



Diffraction pattern of SPs is vary narrow (< 2°) !

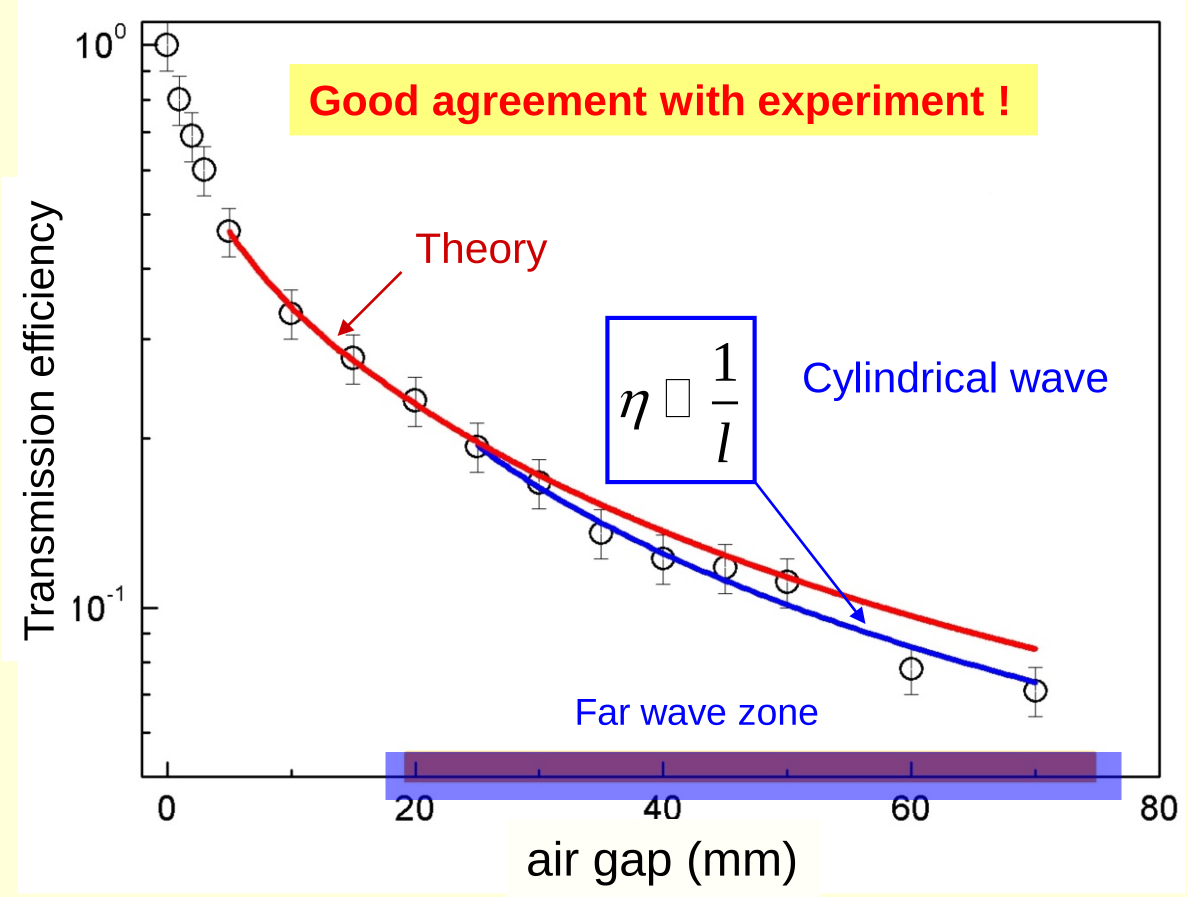
Calculated diffraction patterns are agree with experimental ones

I. A. Kotelnikov, V. V. Gerasimov and B. A. Knyazev
// Phys. Rev. A. 2013. V. 87. P. 023828

Theory and experiment

Transmission efficiency (overlap integral):

$$\eta = \frac{\left|\int_0^\infty B_y(z)\cdot B^*_{ySP}(z)\,dz\right|^2}{\int_0^\infty |B_y(z)|^2\,dz \cdot \int_0^\infty |B^*_{ySP}(z)|^2\,dz}$$



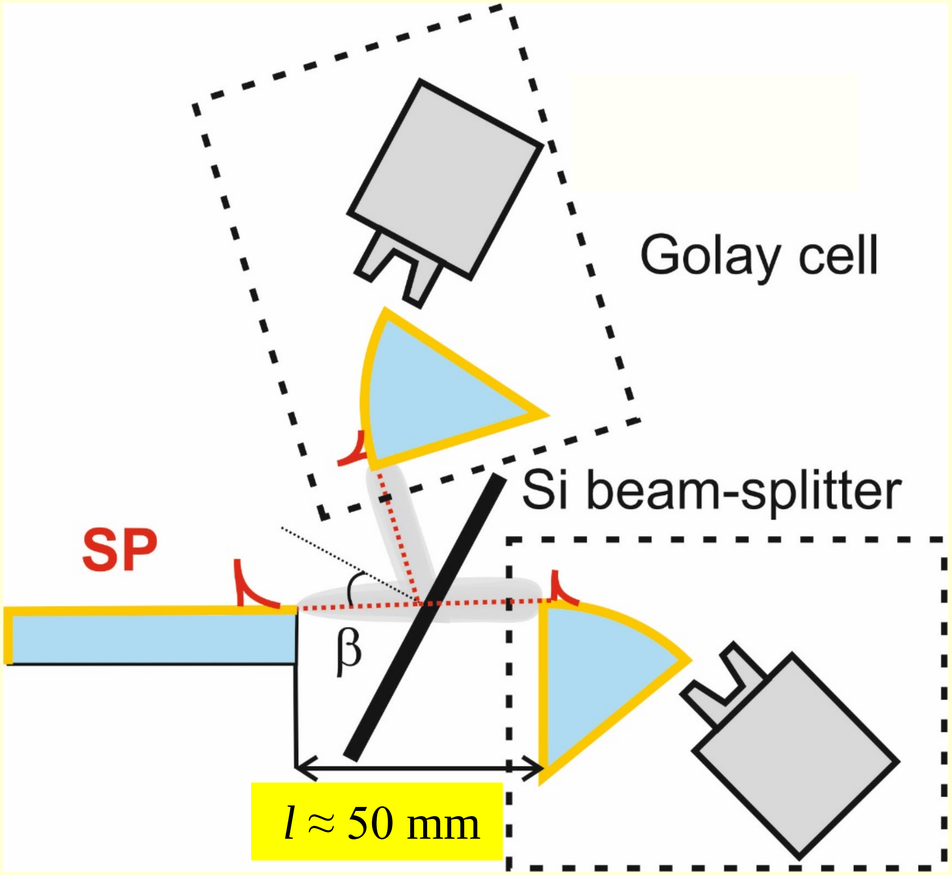
Transmission efficiency of SPs through air gaps: Visible – millimeter region

Surface structure	λ, μm	$L_{1/e}$, μm	$L_{1/e}/\lambda$
Au	0.73	0.9	1.2
Au	0.86	2	2.4
Al	10	2000	200
Au + 0.5 μm ZnS	130	86000	660
Au + 1.5 μm ZnS	130	43000	330
DurAl	630	20000	32

$L_{1/e}$ – transmission efficiency is reduced in ≈2.718 times

In Terahertz region SPs can transmit macroscopic distance!

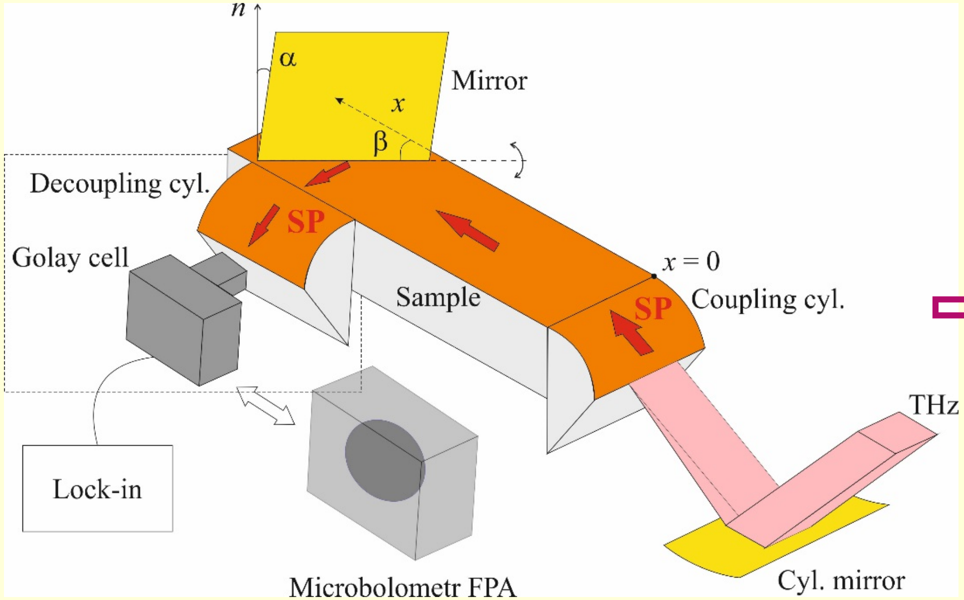
Applications: splitting surface plasmons

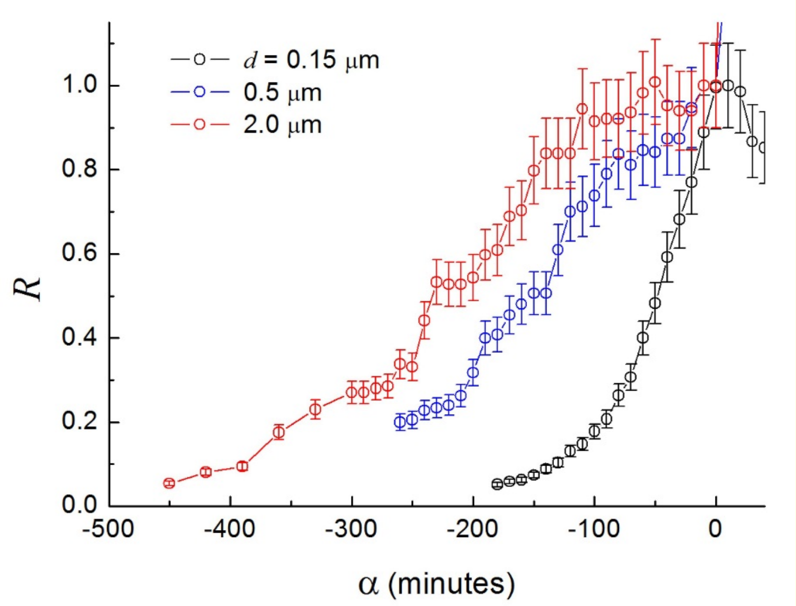


Gerasimov V. V., Knyazev B. A., Nikitin A. K., et al
// Opt. Express 2015, V. 23(26), P. 33448-33459.

It can be useful for developing of THz plasmon interferometer…

Experimentally study of interaction of monochromatic terahertz surface plasmons with plane mirrors





<u>It was experimentally demonstrated:</u>

- that the classical law of reflection is valid for THz surface plasmons (SPs)
- 100% of SP reflection occurs at small tilt angles (α) of the mirror (0 < α < α*)
- At higher angles (α) the SP reflection coefficient (*R*) decreases gradually
- …

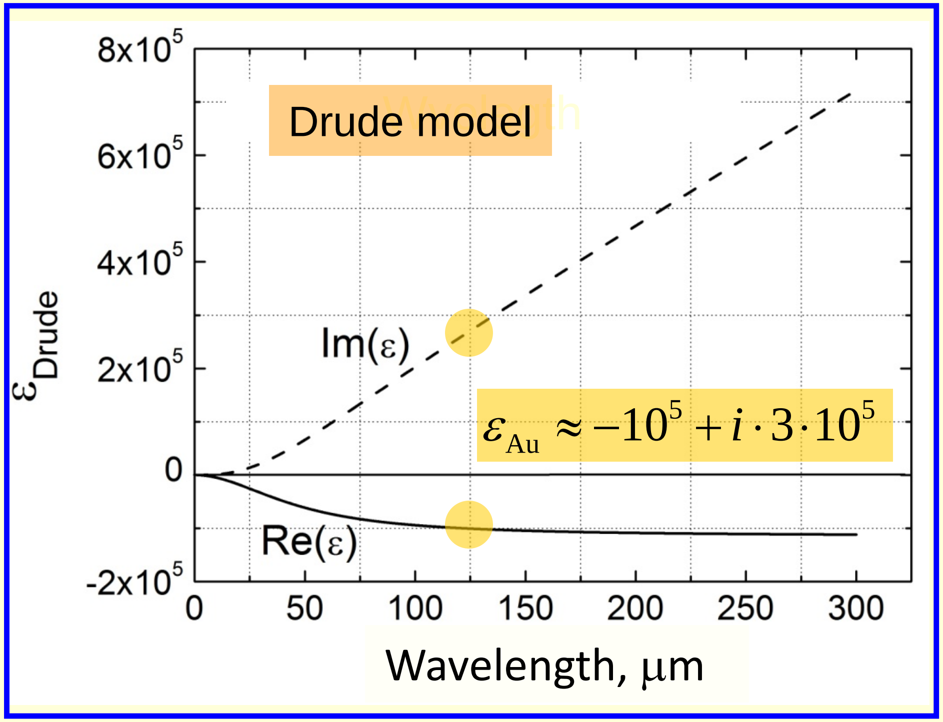
"V. V. Gerasimov, B. A. Knyazev, A. K. Nikitin, Interaction of monochromatic terahertz surface plasmons with plane mirrors (poster - 058)"

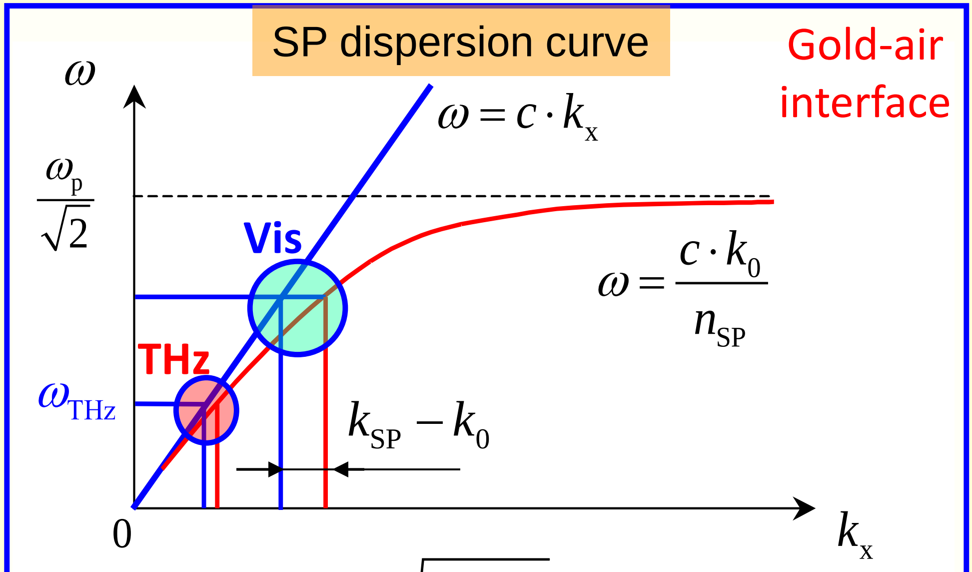
Summary

1. Experimentally demonstrated that "Radiative" losses on surface imperfections play an important role in extinction of terahertz (THz) surface plasmons on plane metal-dielectric interfaces
2. A thin-film dielectric coating about $\lambda/250$ thick could increase by four times the SP propagation length
3. THz SPs can transmit macroscopic air gaps!
4. Experimentally demonstrated that plane mirrors can be used for reflecting SPs
5. Theoretical analysis showed that spoof surface plasmons on corrugated surfaces can be used for biological sensing

Thank you for attention!

Surface plasmons in THz region





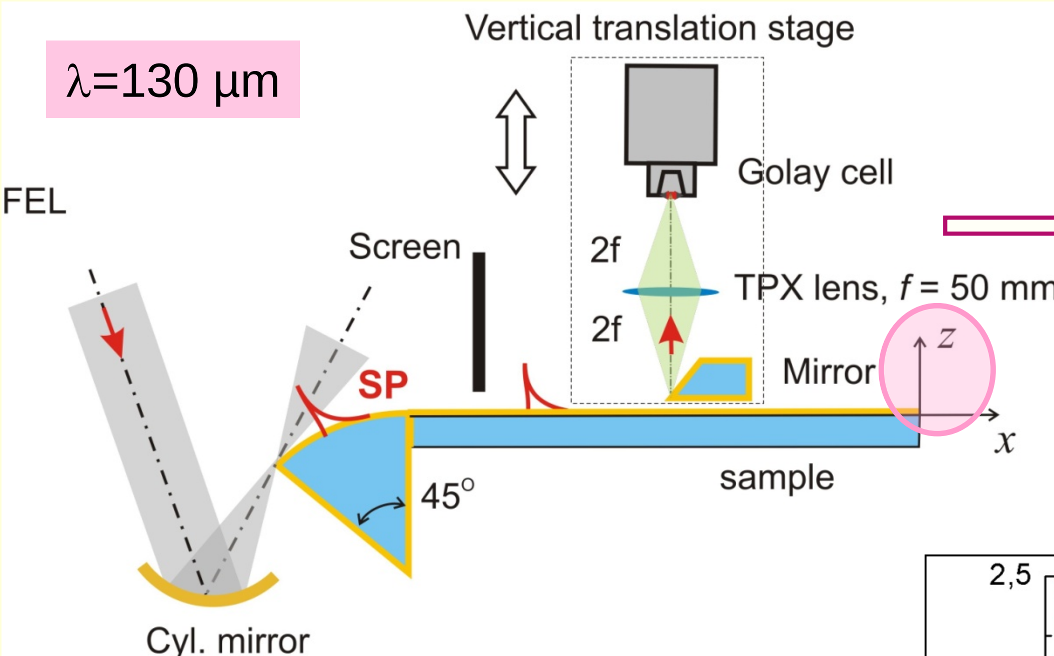
$$\tilde{n}_{SP} = \sqrt{\frac{\varepsilon_m}{\varepsilon_m + 1}} = n_{SP} + i \cdot \kappa_{SP}$$

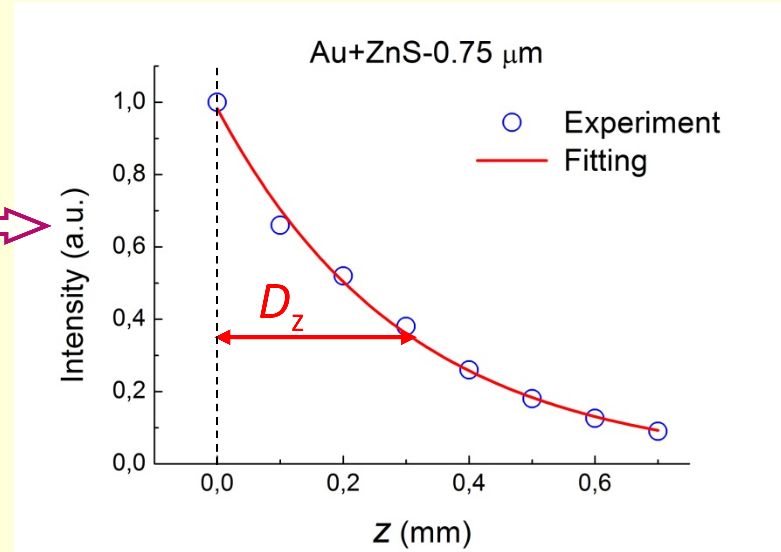
$$(\omega_{THz}, \omega_\tau) \ll \omega_p \quad \rightarrow \quad -\mathrm{Re}(\varepsilon_m), \mathrm{Im}(\varepsilon_m) \gg 1 \qquad n_{SP} - 1 \approx -\frac{1}{2 \cdot \mathrm{Re}(\varepsilon_m)} \approx 10^{-6} \div 10^{-7}$$

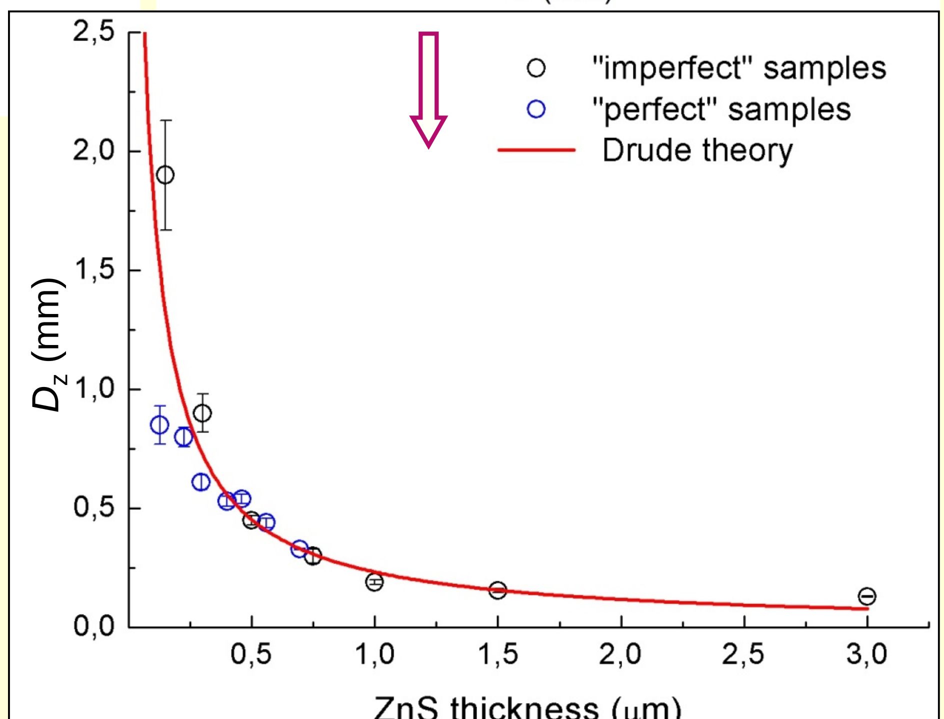
$$\upsilon_{SP}^{\mathrm{phase}} \approx c$$

THz SPs are similar to a free wave, weakly coupled to the guiding surface and can easy transform to a bulk wave on surface imperfections (roughness, impurities, etc.) producing “radiative losses”

Measurement of SP decay length D_z



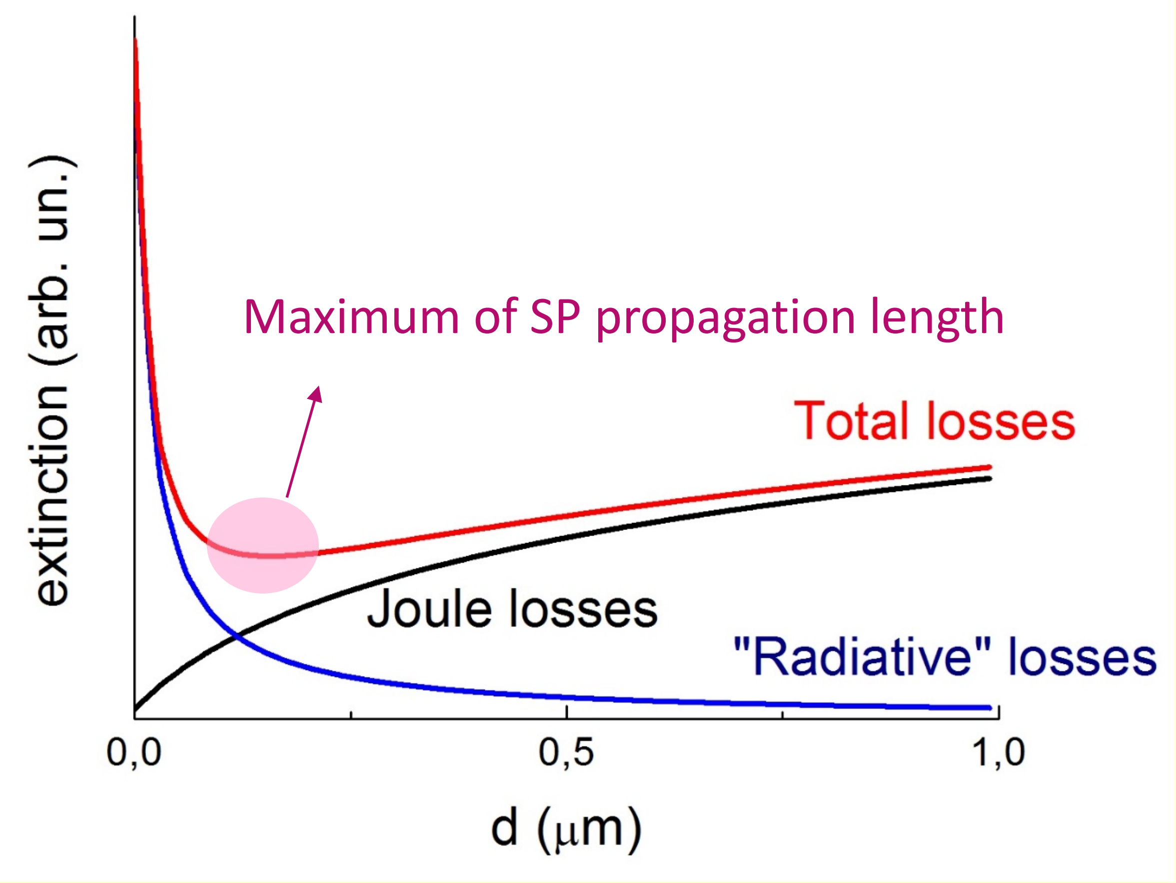




Experimental results well correlated with Drude theory!

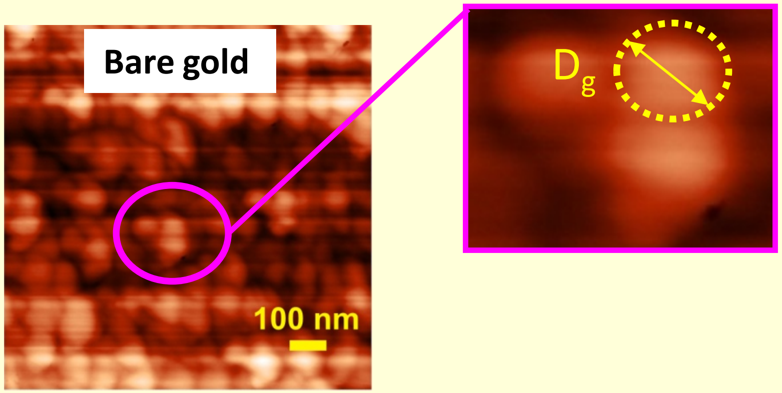
Origin of the maximum of SP propagation length

SP extinction = “Radiative” losses + Joule losses



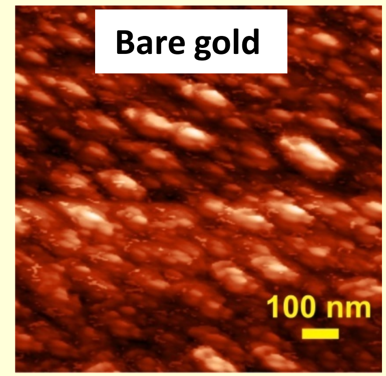
The "perfect" metal-dielectric surfaces have larger Joule losses - possible explanation

"Imperfect" set



Surface AFM-image

"Perfect" set



The mean diameter of grains D_g = 75±30 nm

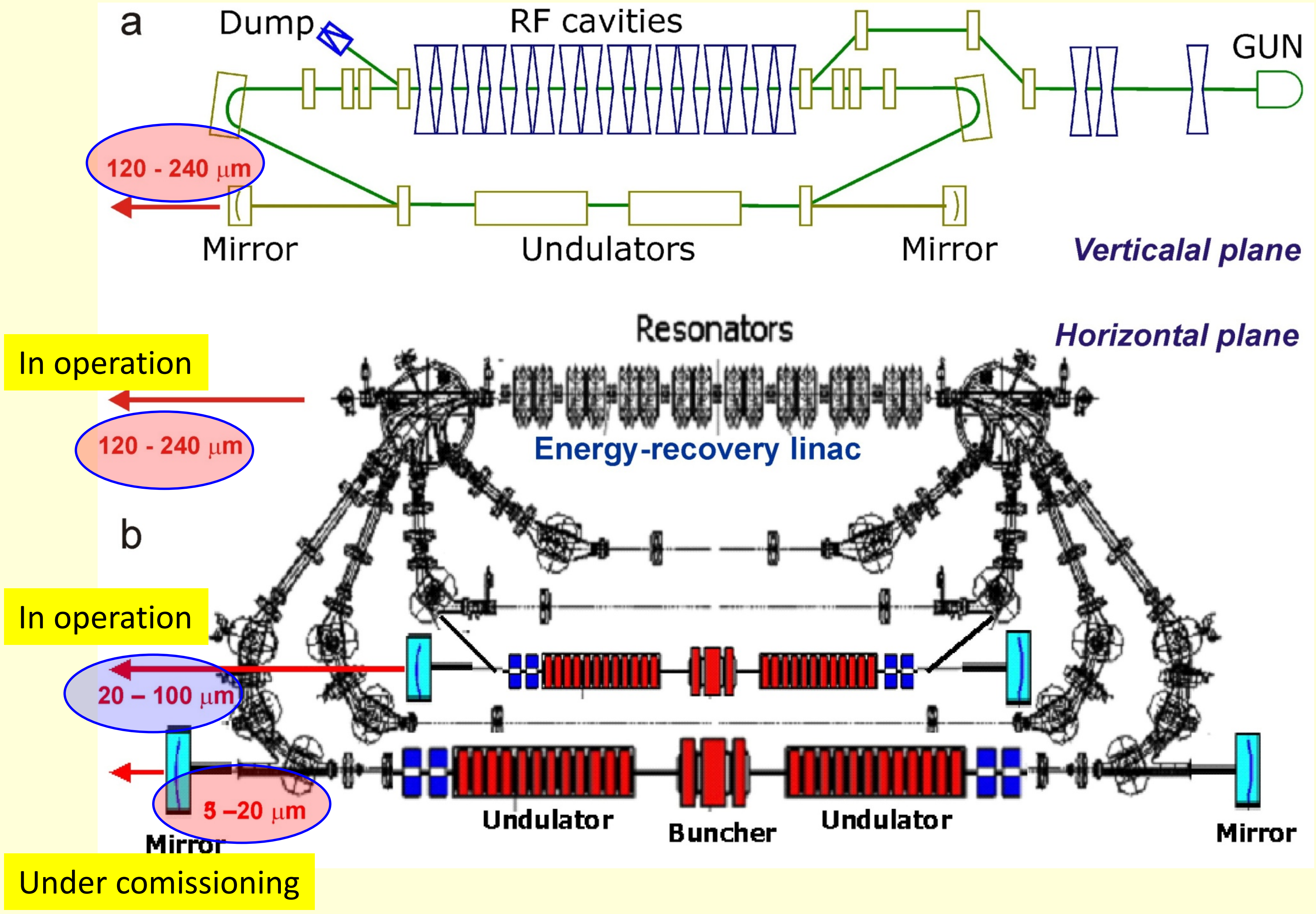
D_g = 30±20 nm

D_g ~ electron free path in gold (l_e≈41 nm)

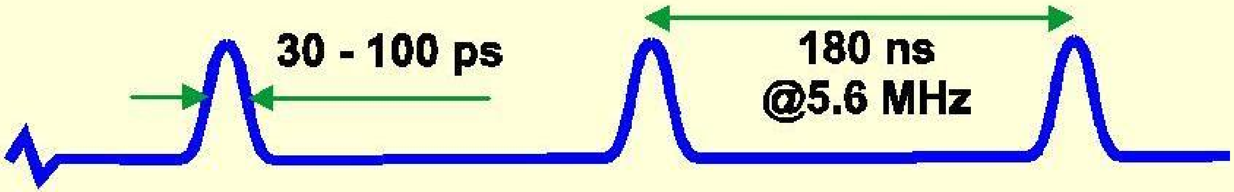
⇩

With decreasing of a grain size (for "perfect" samples), according the Drude model, the electron damping frequency must rise, increasing Joule losses

Novosibirsk free electron laser

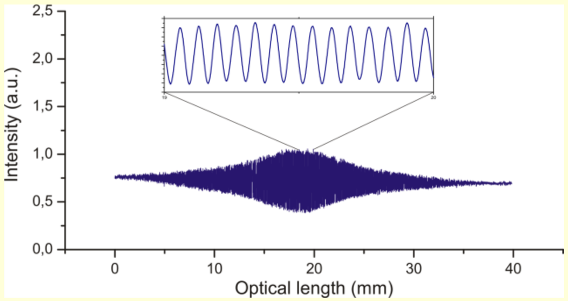


Laser beam characteristics at the user station



Continuous stream of pulses

$$L_{\text{coherence}} \approx 30\,\text{mm}$$



- Wavelength was 130 μm
- Relative linewidth: 0.3 – 1 %
- Beam divergence: $4 \cdot 10^{-3}$ rad
- Linear polarization degree: not less than 99.6%
- Laser beam power was ~ 10 – 40 Watts

NovoFEL: general view

Application of NovoFEL radiation has benefits for SP study:

- no dispersion
- direct measurement (no Fourier transform required)
- high signal to noise ratio
- possibility of real-time imaging of SP

Good agreement between the theory and experiment

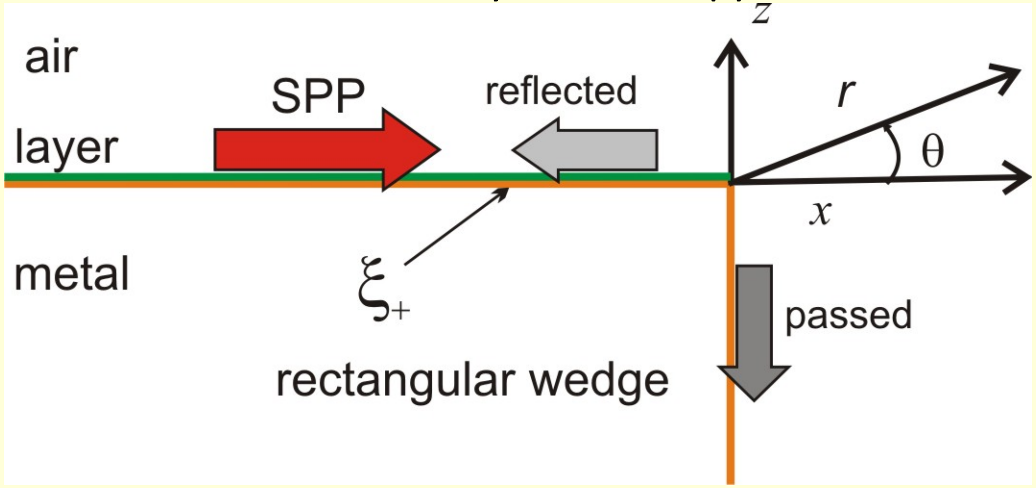
- Diffracted wave width correlated well with calculated SPP decay length
- Diffracted wave possesses a very narrow angular distribution
- Deposition of ZnS layer on the gold surface substantially changes SPP propagation length, decay length and angular distribution of the diffracted wave

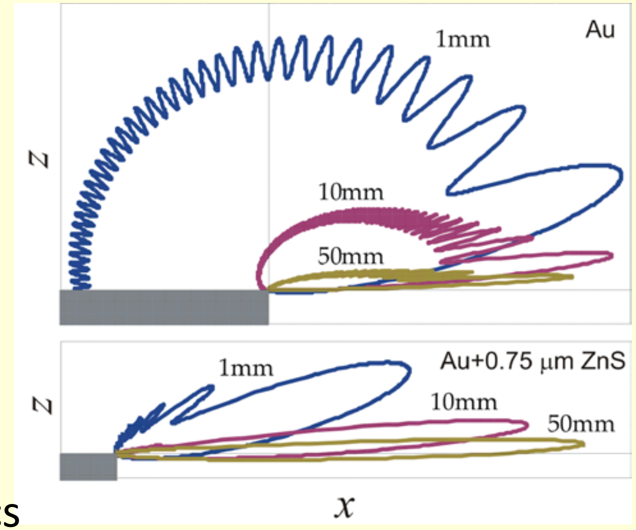
Surface	d_z, mm	L, m	$10^3\xi$	R, cm	$\Delta\theta_{fw}$, deg
Au	16	7.7(0.031)	$1.02 - i \cdot 1.42$	1100	0.16
Au-ZnS(0.25μm)	2	0.95(0.011)	$1.03 - i \cdot 11.3$	17.6	1.3
Au-ZnS(0.75μm)	0.7	0.34	$1.05 - i \cdot 31.2$	3.3	3.6

Drastically discrepancy in the propagation length

Theory of diffraction of SPP

Kotelnikov, V. V. Gerasimov and B. A. Knyazev, Diffraction of surface wave on conducting rectangular wedge, Phys. Rev. A. 2013. V. 87. 023828.
we used Sommerfeld-Malyuzhinets approach





Drude model was applied for calculation of metal characteristics

Analytical solution is valid in both near- and far-field wave zones

$$B(r,\theta) = -\frac{1}{2}\exp(-s^2)\left[-1 + i\,\mathrm{erfi}(s)\right]\exp\left(ik_0 r\right),$$

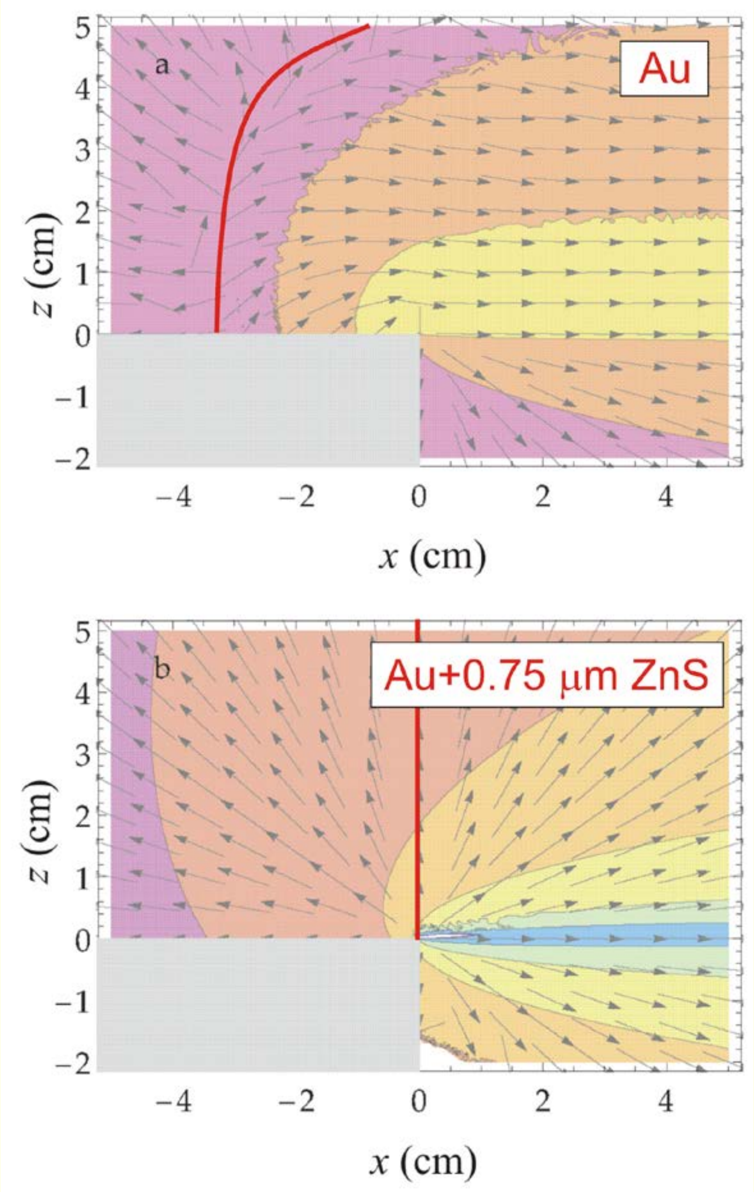
$$\mathrm{erfi}(s) = \frac{2}{\sqrt{\pi}}\int_0^s \exp\left(t^2\right)dt, \qquad s = \frac{1+i}{2}\left(\theta + \chi_+\right)\sqrt{k_0 r}$$

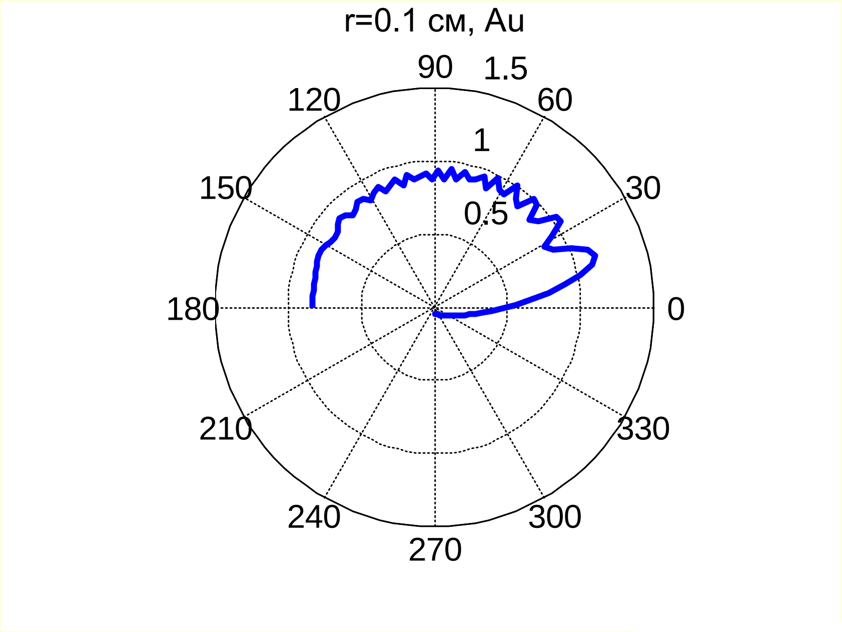
$$\mathbf{E} = \frac{i}{k}\mathrm{rot}\mathbf{B}, \qquad \mathbf{S} \propto \mathbf{E} \times \mathbf{B}^* \qquad \chi_+ = \arcsin\left(\xi_+\right)$$

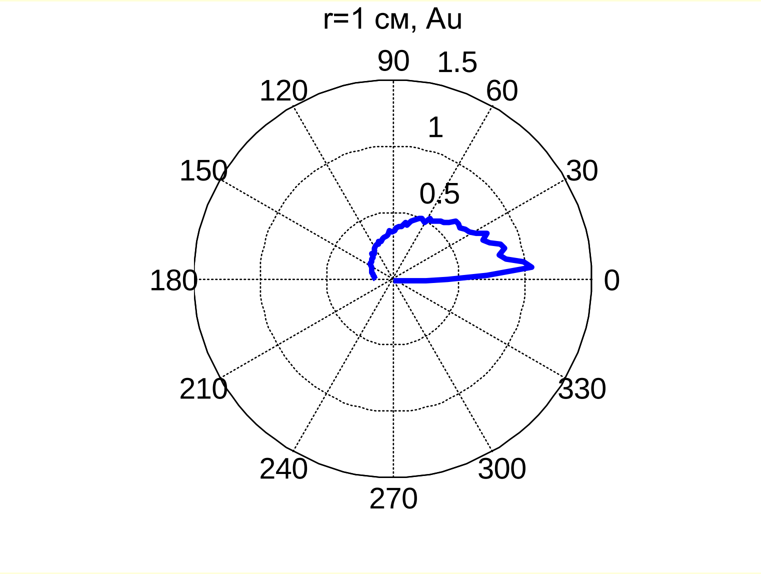
Main implications:

1. **If $\mathrm{Re}(\xi_+)>0$, intensity of the reflected and refracted SPP are much less then incident SPP (can be neglected)**
2. **If $|\xi_+| \ll 1$ far-field wave zone lies at**
   $r \gg R \approx k_0^{-1}|\mathrm{Im}\xi_+|^{-2}$ **(meters for bare gold)**
3. **In the far-field angular distribution is Lorenzian with** $\Delta\theta_{\text{св}} \approx 2|\mathrm{Im}$

Diffraction of SPP: Pointing vector




r=0.1 см, Au
90
1.5
120
60
1
150
30
0.5
180
0
210
330
240
300
270


r=1 см, Au
90
1.5
120
60
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330
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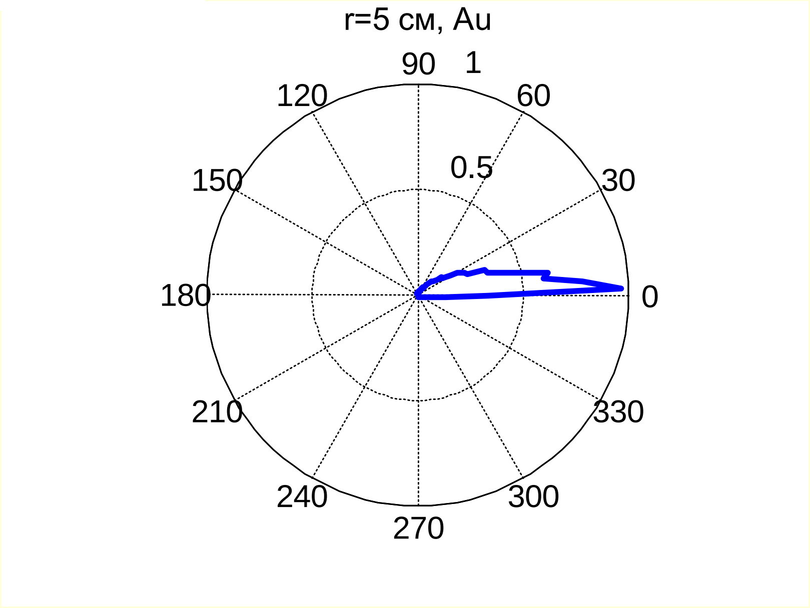
r=5 см, Au
90
1
120
60
0.5
150
30
180
0
210
330
240
300
270