Maximal energy coupling to complex plasmonic devices by injecting light into eigenchannels

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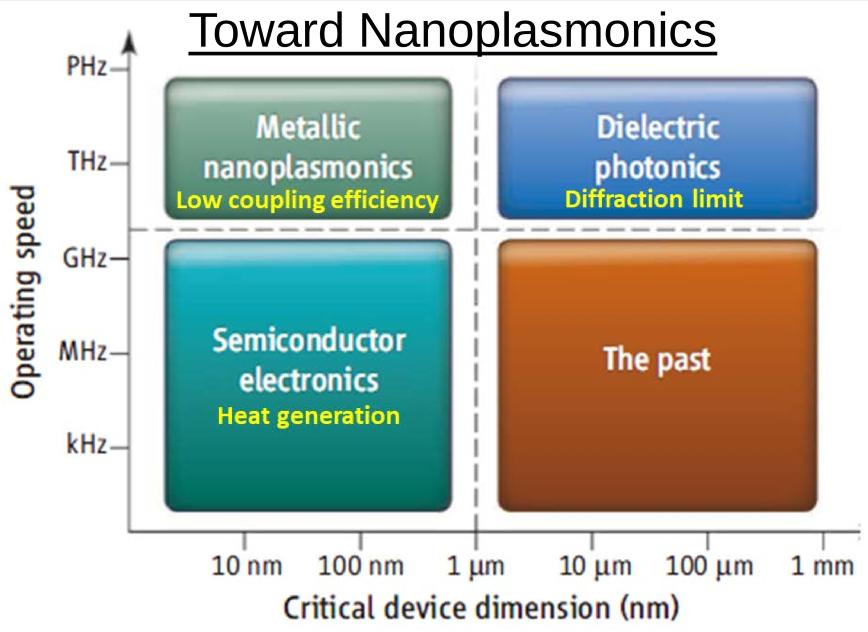
Abstract

Surface plasmon polaritons have attracted broad attention in the optoelectronics field due to their ability to merge nanoscale electronics with high-speed optical communication. As the complexity of optoelectronic devices increases to meet various needs, this integration has been hampered by the low coupling efficiency of light to plasmonic modes. Here we present a method to maximize the coupling of far-field optical waves to plasmonic waves for arbitrarily complex devices. The method consists of experimentally identifying the eigenchannels of a given nanostructure and shaping the wavefront of incident light to a particular eigenchannel that maximizes the generation of plasmonic waves. Our proposed approach increases the coupling efficiency almost four-fold with respect to the uncontrolled input. Our study will help to facilitate the integration of electronics and photonics.

Introduction

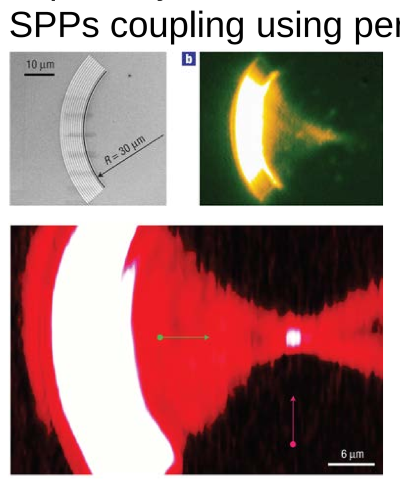
Toward Nanoplasmonics

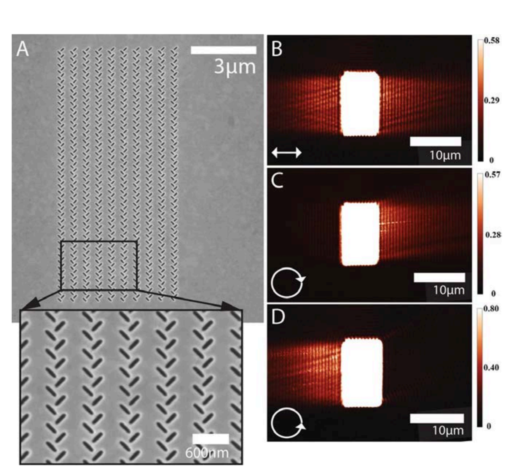


- Potential solution : Photonics + Electronics -> Opto-electronics
- It is necessary to increase the coupling efficiency

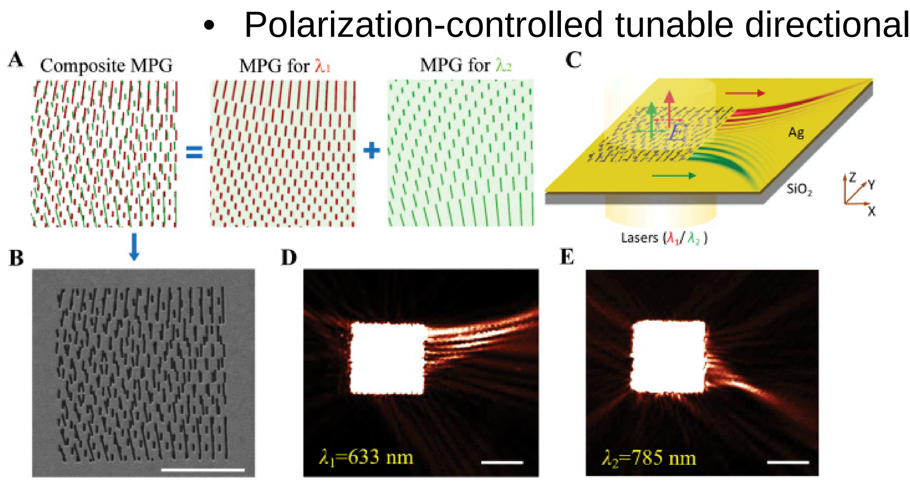
Conventional plasmonic devices

- Lopez-Tejeira, F. et al. Nat Phys 3, 324-328 (2007)
- SPPs coupling using periodic band-gap structures





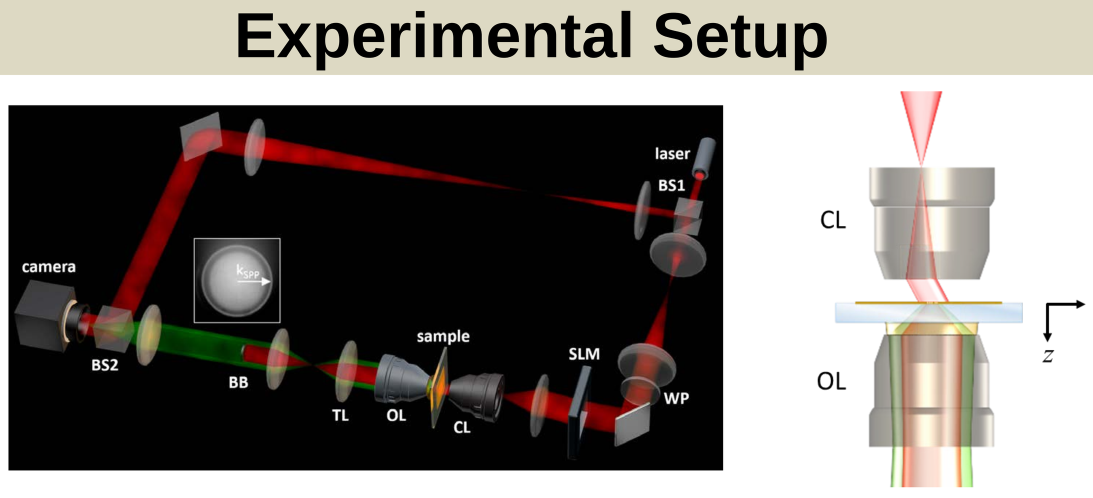
- Lin, J. et al. Science 340, 331-334 (2013)
- Polarization-controlled tunable directional coupling of SPPs



- Lin, J. et al. Sci Rep 5:10529 (2015)
- Multiplexing of SPPs using mode-matching metasurfaces

- While these approaches hold great promise for promoting an increase in the complexity of devices, the coupling efficiency drops as the number of band-gap structures increases.

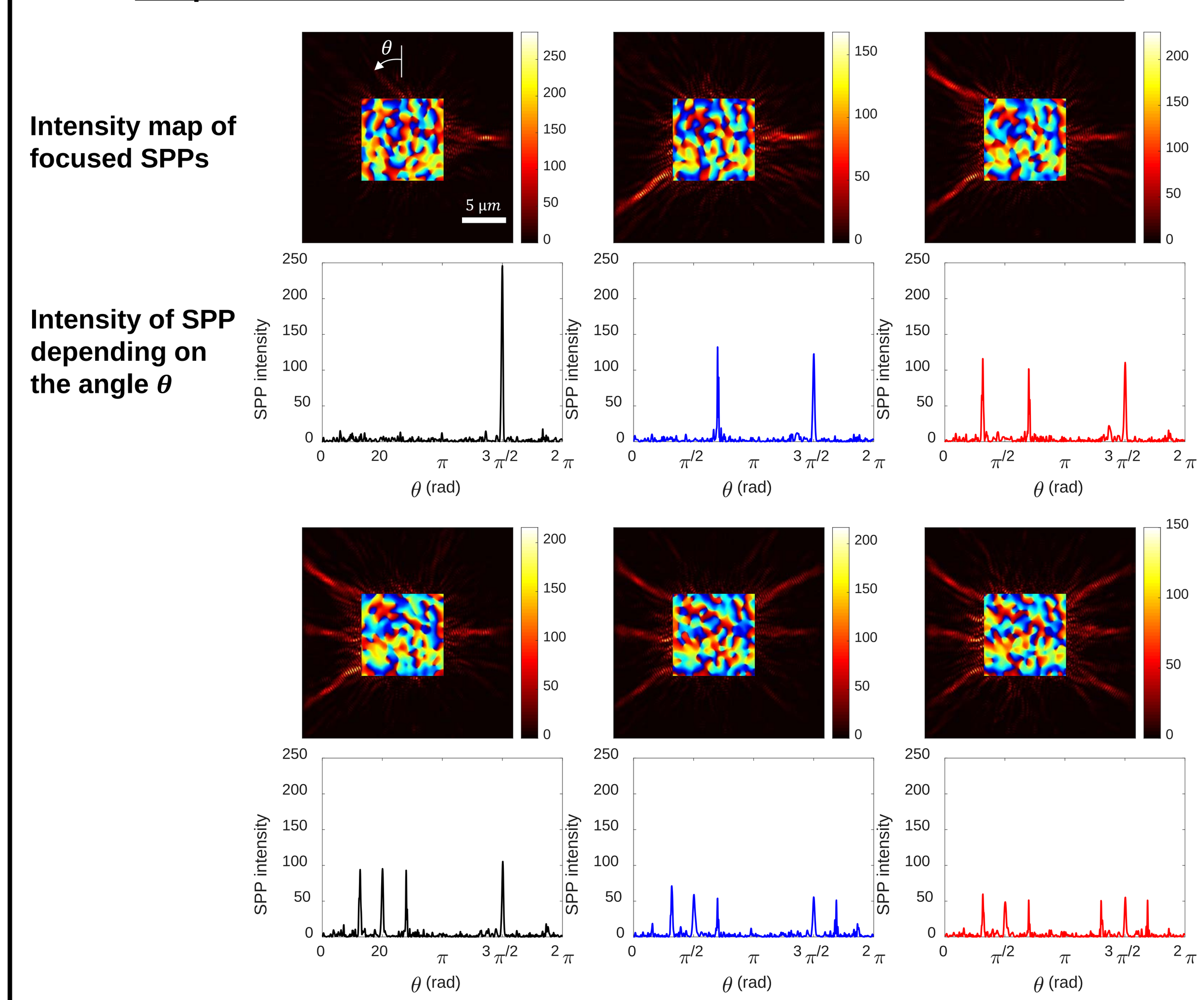
Experimental Setup



- BS : beam splitter, WP : quarter-wave plate, CL : condenser lens, OL: objective lens, TL : tube lens, BB: beam block plate
- Leakage radiation microscope (LRM) to measure the SPPs leaked from the air/gold interface
- Phase microscope to record the phase and amplitude of the SPP
- Spatial light modulator (SLM) for wave-front shaping of incident wave

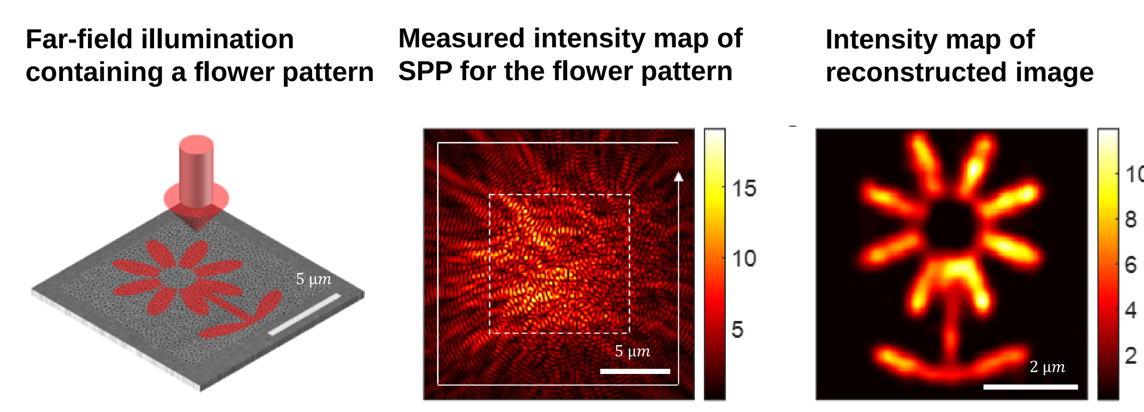
Previous result

Experimental Demonstration of MIMO Network



- We demonstrated the transfer of more than 40 far-field input channels to the SPPs
- With the increased transmission channel number, we implemented the simultaneous control of 6 SPP channels at high signal-to-noise ratios

Imaging Delivery of 2D Far-field Image to 1D SPPs Sampling Line

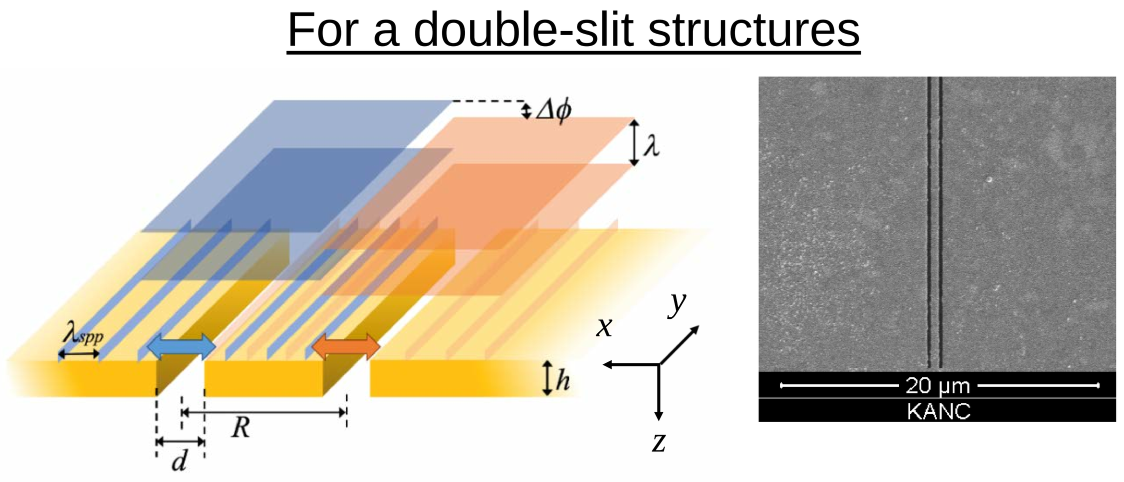


- We demonstrated the delivery of far-field 2D image information to 1D SPP output channels

W. Choi, Y. Jo et al., Nature Communications 8:14636 (2017)

Analytical approach

For a double-slit structures



$$(G_S - \Sigma)E_l + G_D(R)E_r - G_\nu E_l' = E_l^{in}$$

$$(G_S - \Sigma)E_l' + G_D(R)E_r' - G_\nu E_l = 0$$

$$(G_S - \Sigma)E_r + G_D(R)E_l - G_\nu E_r' = E_r^{in}$$

$$(G_S - \Sigma)E_r' + G_D(R)E_l' - G_\nu E_r = 0$$

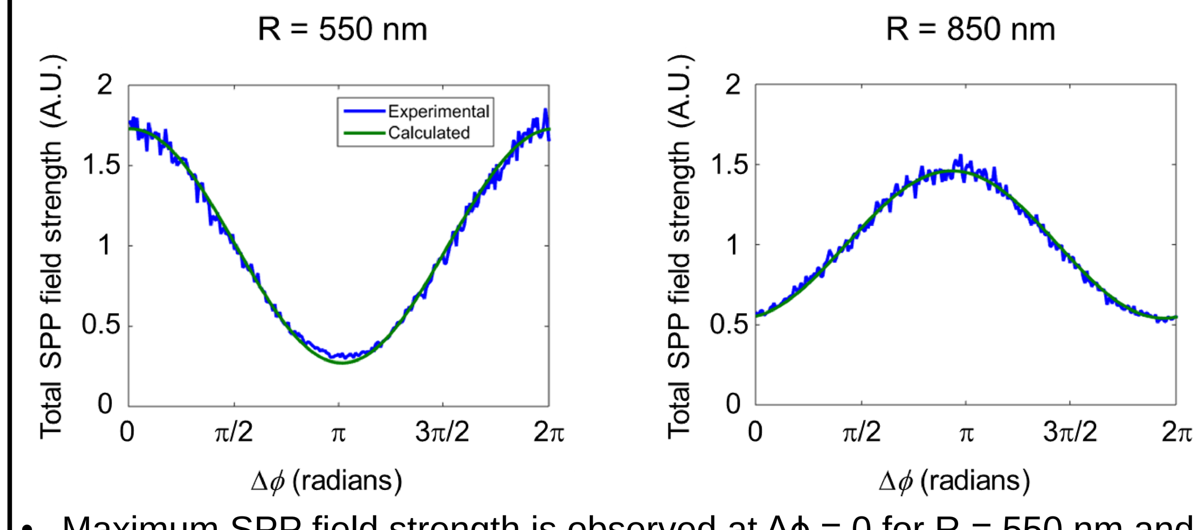
$$\begin{pmatrix} E_l \\ E_r \end{pmatrix} = \begin{pmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{pmatrix} \begin{pmatrix} E_l^{in} \\ E_r^{in} \end{pmatrix}$$

$$E_r^{in} = E_l^{in} e^{i\Delta\phi}$$

$$|E_l|^2 + |E_r|^2 \propto 1 + a e^{-\xi R} \cos(k_{spp} R) \cos \Delta\phi$$

- The separation R determines whether the symmetric or anti-symmetric coupling of the incident wave is optimal

Total SPP field strength and the phase difference of the incident wave

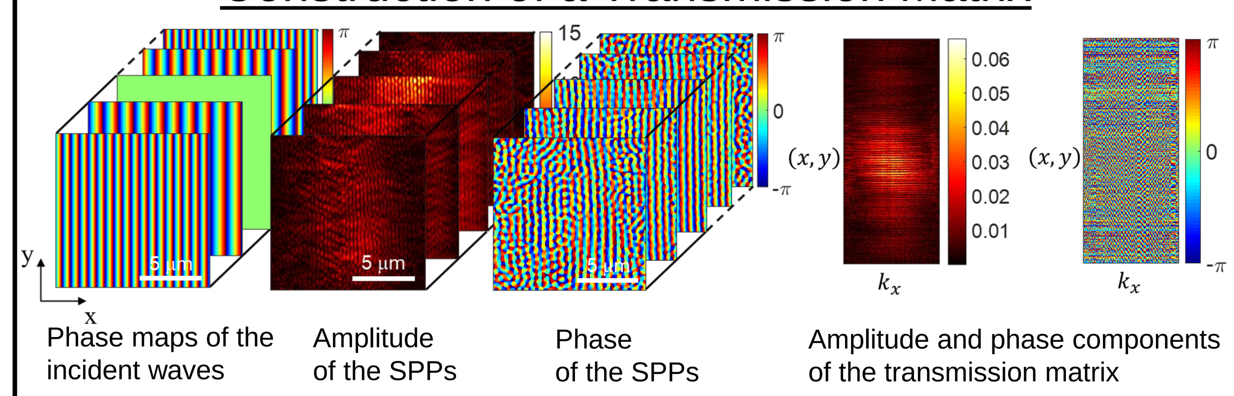


- Maximum SPP field strength is observed at Δϕ = 0 for R = 550 nm and Δϕ = π for R = 850 nm
- The extended CMM can accurately predict the incident wave that maximizes the generation of SPPs

- Analytical approach is limited to well-defined structures, and its extension to more complex structures tends to be extremely difficult because the analytic expressions become too complicated

Eigenchannel coupling approach

Construction of a Transmission Matrix



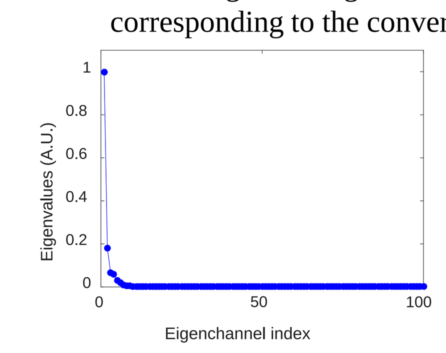
Singular Value Decomposition

$t = U\tau V^{+}$

U : unitary matrix containing the eigenvectors for the SPPs

V : unitary matrix containing the eigenvectors for the far-field input

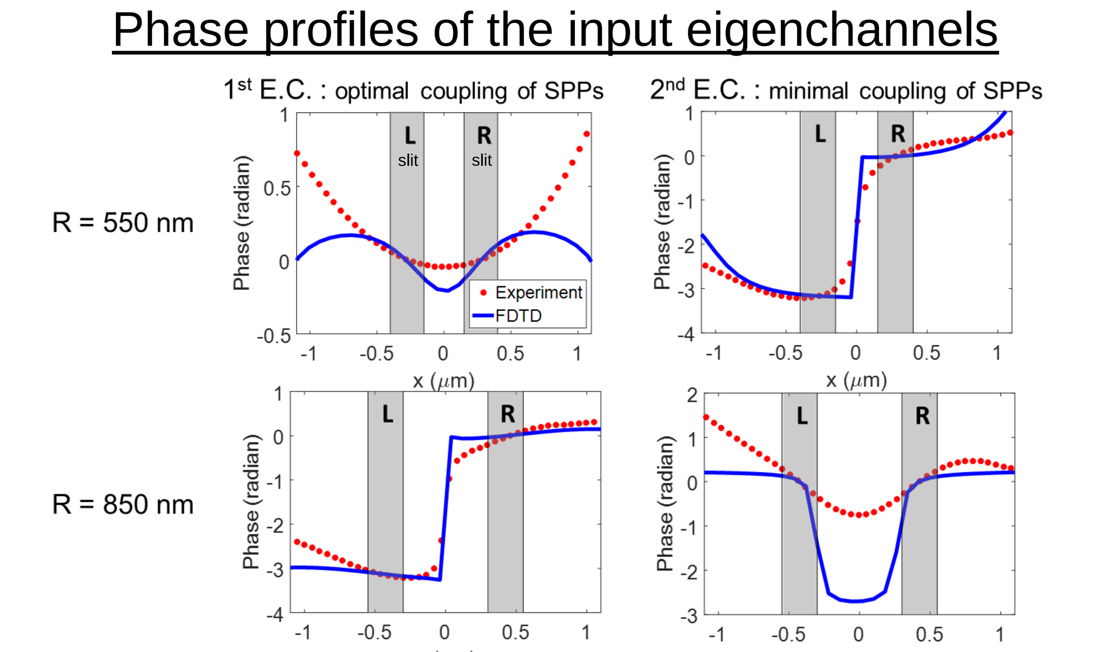
τ : non-negative diagonal matrix containing the singular values corresponding to the conversion efficiency from far-field waves to SPPs



eigenvalue = (singular value)^2

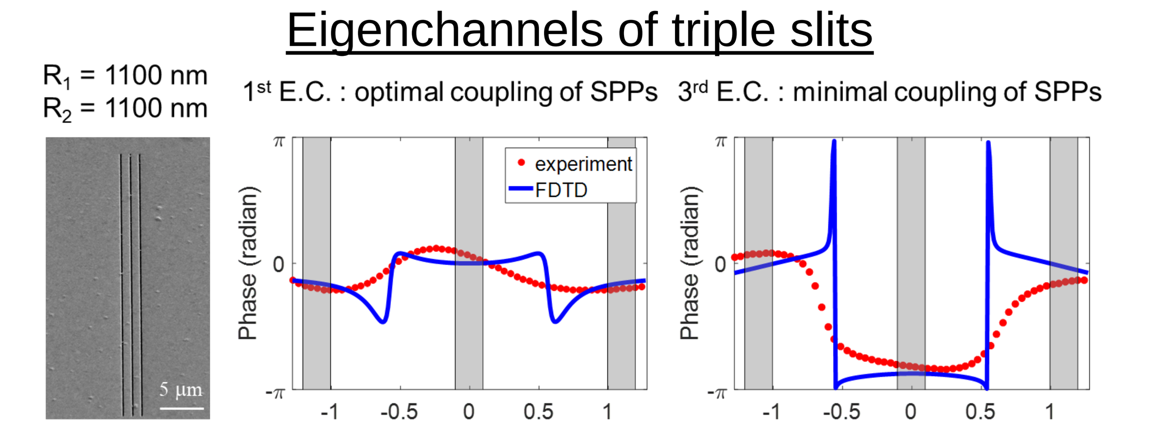
- Because the two small slits each had only a single fundamental mode, there were only two meaningful eigenvalues

Phase profiles of the input eigenchannels

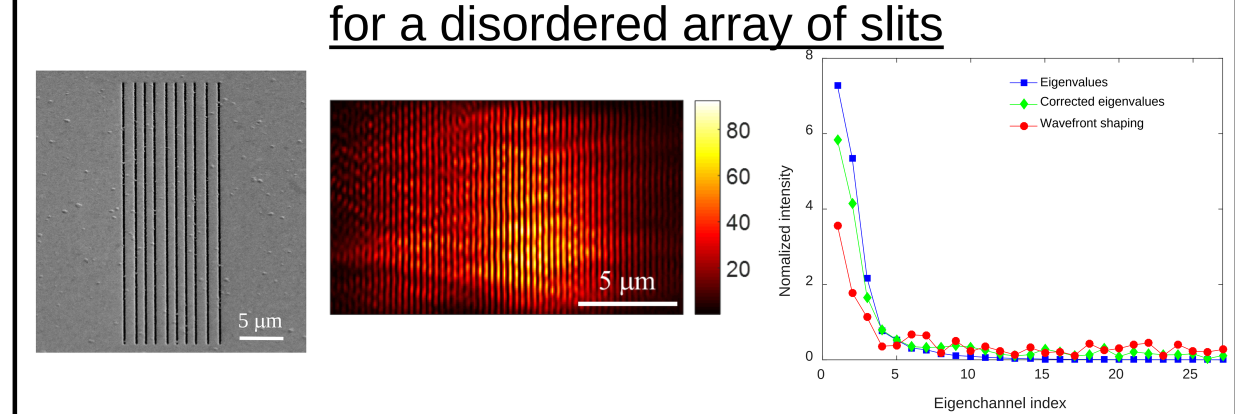


- For R = 550 nm, the phase values at the left- and right-hand slits were almost the same, i.e. Δϕ ≈ 0. On the other hand, the phase values at the slits differed by almost π for R = 850 nm
- These results agree with the result of FDTD simulation and the predictions made by both the analytical approach and the direct phase modulation experiment
- These results confirm that the identification of eigenchannels is a systematic approach to determining the optimal (and minimal) coupling conditions for the generation of SPPs.

Eigenchannels of triple slits



Maximal coupling to SPPs for a disordered array of slits



- For this type of sample, it is almost impossible to predict the incident wave that can maximize the generation of SPPs
- In comparison with the normally incident plane waves, we observed that the SPPs were close to four times stronger

Y. Jo, W. Choi et al., Scientific RePortS 7: 9779 (2017)

Conclusions

- We constructed an experimental setup to measure the transfer matrix from far-field inputs to SPP outputs.
- By shaping the wavefront of the incident wave, we have demonstrated that the coupling efficiency of far-field waves to SPPs can be 4 times higher for arbitrarily complex nanostructures.
- Our method of efficiently coupling far-field waves to SPPs for any arbitrarily complex nanostructure may relive the constraints in design freedom and expedite the development of multi-functional plasmonic devices.