

Metamaterials & Plasmonics

Exploring the Impact of Rotating Rectangular Plasmonic Nano-hole Arrays on the Transmission Spectra and its Application as a Plasmonic Sensor.

Abstract—Plasmonic nano-structures play a significant role in most recent photonic devices and applications. In this paper, we investigate the optical transmission spectra of rotatable periodic nano-metric apertures with different dimensions. This investigation includes monitoring the modification of both the transmission resonance wavelengths and peak transmittance at different dimensions and orientations of the nano-holes. The obtained results provide better insight to the interaction of light with periodic plasmonic nano-hole arrays. We find that nano-holes dimension/orientation can totally suppress an optical transmission, tune its resonance wavelengths, and change its peak values. Furthermore, we present the surface plasmonic resonance sensing as an application for the reported nano-hole array. [1]

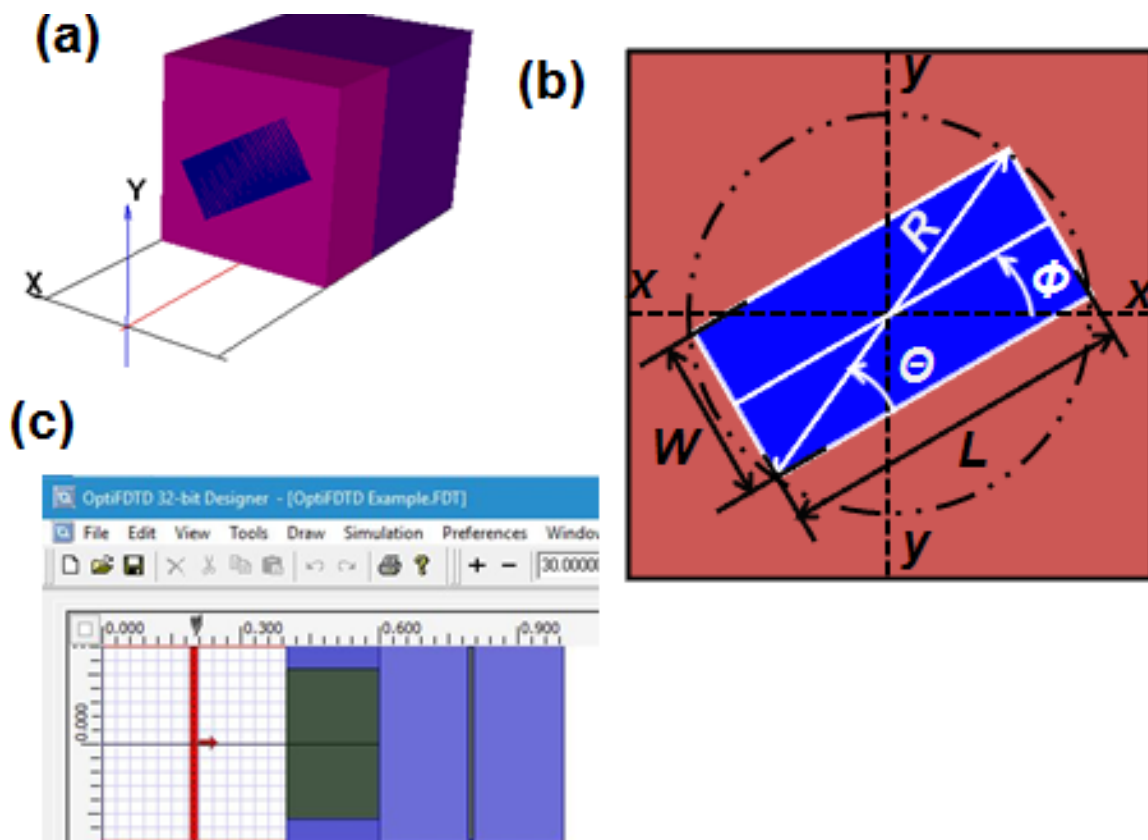


Figure 1: (a) OptiFDTD single cell 3D layout model, (b) A cross section plan view through the rotatable nano-hole, and (c) OptiFDTD layout of the single cell.



Project Layout

The designed plasmonic structure layout is a nano-hole array perforated in gold thin film “sandwiched” between glass substrate and air cladding. The structural periodicity is 425 nm and the gold film thickness is 200 nm.

1. The glass Substrate

The image displays four windows from the OptiFDTD software interface, illustrating the setup of a glass substrate layer.

Top Left Window (Material Properties): Shows the material definition for a layer with refractive index $n=1.5$. The material is set to Isotropic. The refractive index is defined as $\text{Re}: 1.5$ and $\text{Im}: 0$. The wavelength is set to 1.55 μm .

Top Right Window (Channel_SiO2 Profile Definition): Shows the 2D profile definition for a layer named "Channel_SiO2". The material is set to $n=1.5$. The 3D profile definition table is as follows:

Layer Name	Width	Thickness	Offset	Material
Layer 1	0.425	0.425	0.0	$n=1.5$

The layer name is "Layer 1", width is 0.425, thickness is 0.425, and offset is 0.0. The material is $n=1.5$. Slanted Walls are set to 90 degrees for both left and right angles.

Bottom Left Window (Linear Waveguide Properties): Shows the properties for a linear waveguide. The horizontal expression is $x + 0.6 = 0.6$ and the vertical expression is $y + 0 = 0$. The channel thickness tapering is set to Linear, with start and end values of 0.425000. The width is 0.425, depth is 0, and the label is "Substrate". The profile is "Channel_SiO2".

Bottom Right Window (Linear Waveguide Properties): Shows the properties for a linear waveguide. The horizontal expression is $x + 1 = 1$ and the vertical expression is $y + 0 = 0$. The channel thickness tapering is set to Linear, with start and end values of 0.425000. The width is 0.425, depth is 0, and the label is "Substrate". The profile is "Channel_SiO2".



2. The gold Film

Gold_Au_Lorentz_Drude_Model

Name: Gold_Au_Lorentz_Drude_Model

☐ Lorentz Dispersive ☐ Drude Dispersive ☒ Lorentz-Drude Dispersive

☐ Lorentz Drude Dispersive

☐ Use Wavelength ☒ Use Frequency

☒ Isotropic ϵ_{∞} (F/m): 1

Resonance: 6

Resonance	S	P(rad/s)	R(rad/s)	D(rad/s)
1	7.600000e-001	1.371880e+016	0.000000e+000	8.052020e+013
2	2.400000e-002	1.371880e+016	6.304880e+014	3.661390e+014
3	1.000000e-002	1.371880e+016	1.260980e+015	5.241410e+014
4	7.100000e-002	1.371880e+016	4.510650e+015	1.321750e+015
5	6.010000e-001	1.371880e+016	6.538850e+015	3.789010e+015
6	4.384000e+000	1.371880e+016	2.023640e+016	3.363620e+015

Channel_Au

Profile name: Channel_Au

2D profile definition:

Material: Gold_Au_Lorentz_Drude_Model

3D profile definition:

Layer Name	Width	Thickness	Offset	Material
Layer 1	0.425	0.425	0.0	Gold_Au_Lorentz_Drude_Model

Layer name: Layer 1

Width: 0.425

Thickness: 0.425

Offset: 0.0

Material: Gold_Au_Lorentz_Drude_Model

☐ Slanted Walls

Left Slant Angle: 90

Right Slant Angle: 90

Linear Waveguide Properties

Start End

Horizontal Expression: f_x Offset: 0.4 Position: 0.4

Vertical Expression: f_x Offset: 0 Position: 0

Channel Thickness Tapering

☐ Use Default (Channel:None) Taper: Linear

Start: 0.425000 End: 0.425000

Width: 0.425

Depth: 0

Label: Film

Profile: Channel_Au

3. The nano-holes

The nano-holes have a rectangular shape and inscribed in identical circles of 326 nm diameter (D). The structural periodicity is 425 nm and the gold film thickness is 200 nm. Dimensions of the rectangle structures are determined by unequal scaling angle (θ) and the radius of the reference circular structure. The holes are oriented at angle (Φ) with respect to the radial direction.

$$L = D \cos(\theta)$$

$$W = D \sin(\theta)$$



OptiFDTD

Finite-Difference Time-Domain
Simulation Design

 **Optiwave**
DESIGN SOFTWARE

Air

Store | Default | Sync | Cancel | Help

Name: Air ☒ Default

☒ Isotropic ☐ Anisotropic

Isotropic

Refractive index: Re: 1 Im: 0

☐ Sellmeier

Wavelength: 1.55 [um] Calculate

Channel_Air

Store | Default | Sync | Cancel | Help

Profile name: Channel_Air ☐ Set default ☐ Default

2D profile definition

Material: Air

3D profile definition

Layer Name	Width	Thic...	Offset	Material
Layer 1	0.425	0.425	0.0	Air

Layer name: Layer 1

Width: 0.425

Thidgness: 0.425

Offset: 0.0

Material: Air

☐ Slanted Walls

Left Slant Angle: 90

Right Slant Angle: 90

Block Waveguide Properties

OK | Cancel | Help

Transformation parameters

Position

X (um) 0 = 0

Y (um) 0.2125 = 0.2125

Z (um) 0.5 = 0.5

Orientation

Azimuth (deg) 0 = 0

Elevation (deg) 0 = 0

Rotation (deg) orientation = 45

Shape Configuration

Block - full definition

Shape's clipping plane count N/A

Copy shape planes to user-defined Copy

Vector1 (0, 0, Z)

Z (um) 0.2 = 0.2

Vector2 (X, 0, Z)

X (um) 0.326*cos(unequal*PI/180) = 0.230516810E

Z (um) 0 = 0

Vector3 (X, Y, Z)

X (um) 0 = 0

Y (um) 0.326*sin(unequal*PI/180) = 0.230516810E

Z (um) 0 = 0

Label: Hole

Clipping Planes...

Material: Air

Material In Use...

Variables and Functions

OK | Cancel | Help

User Variable | User Function | DLL Function

User variable declaration

Name:

Expression:

Value:

Verify Add/Apply

User Variables | User Functions/DLLs

User Variable	Expression
1 unequal	45
2 Pi	3.141592654
3 orientation	45

Delete



Design VB script code to scan the unequal scaling and orientation angles

For i = 1 to 13

select case i

case 1

orientation = 0

unequal = 10

case 2

orientation = 0

unequal = 25

case 3

orientation = 0

unequal = 45

case 4

orientation = 0

unequal = 55

case 5

orientation = 30

unequal = 10

case 6

orientation = 60

unequal = 10

case 7

orientation = 90

unequal = 10

case 8

orientation = 30

unequal = 25

case 9

orientation = 60

unequal = 25

case 10

orientation = 90

unequal = 25

case 11

orientation = 15

unequal = 45

case 12

orientation = 30

unequal = 45

case 13

orientation = 45

unequal = 45

end select

ParamMgr.SetParam "unequal", unequal

ParamMgr.SetParam "orientation",

orientation

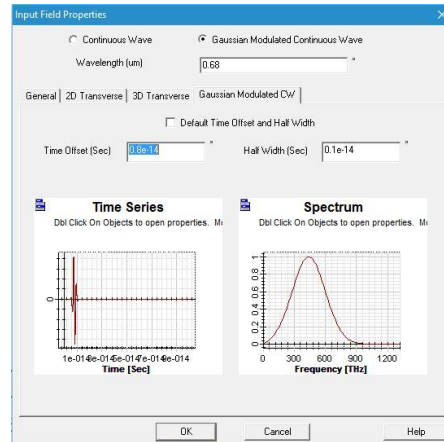
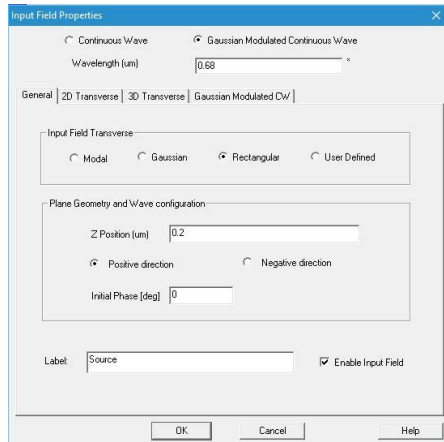
WGMgr.Sleep 500

ParamMgr.Simulate

Next

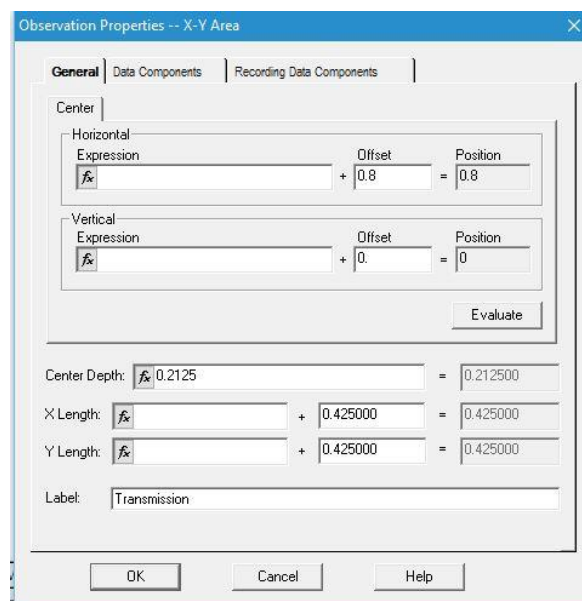
Define Input Source

In order to realize a broadband simulation on the dispersive gold film, Gaussian modulated electromagnetic plane wave source was used. The continuous waves are centered at 680 nm, linearly polarized in y -direction, and convoluted with a Gaussian envelope function. In the time domain, the light pulse has a half width of 0.8×10^{-14} s and an offset time of 0.1×10^{-14} s. The simulation is performed at normal incidence (z -direction) of the plane wave through the nano-hole arrays.



Define observation area

An observation area will perform and calculate the transmission spectral analysis at 400 nm away from the air/Au film interface.



Simulation parameters and boundary conditions

The simulation cell is 425 nm × 425 nm × 1000 nm in the Cartesian coordinates x, y, and z. An absorbing boundary condition was rendered in the z-direction using anisotropic perfect matching layer, while, periodic boundary conditions were used in the x and y directions. The mesh size is adjusted to be small enough to catch the wave attenuation within the skin depth. As a result, the calculation mesh resolution is set as 5 nm ($< 0.1 \lambda$) to get accurate results. The simulation is executed through 12,000 time step for a calculation time of 100 fs.



3D Simulation Parameters

Mesh Parameters:

Mesh Delta X (um) [0.005] Number of Mesh Cells X [95] ☐ Auto
Mesh Delta Y (um) [0.005] Number of Mesh Cells Y [95] ☐ Auto
Mesh Delta Z (um) [0.01] Number of Mesh Cells Z [100] ☐ Auto

The minimum memory requirement is: 111.31M bytes.
Wafer Dimensions: 1.00 um (length) * 0.42 um (width) * 0.42 um (depth)

Time Parameters:

Time Step Size: [8.3391023799538e-018] ☒ Auto
☒ Run for [12000] Time Steps (Results Finalized) ☐ Auto
☐ Run Until User Stops Execution, then Finalize Results

Nonuniform Mesh Parameters:

☐ Use Nonuniform Mesh Parameters...

Script Option: ☐ Simulate Using Script ☐ Simulate Using Sweep

Key Input Field: [Source and wavelength: 0.68]

DFT Options:

Components for Post-Simulation Analysis:

Electric Components: ☐ Ex ☐ Ey ☐ Ez
Magnetic Components: ☐ Hx ☐ Hy ☐ Hz

Time Sampling Interval: [1] ☐ Auto

Run... Summary... OK Cancel Help

Boundary Conditions

Boundary Conditions:

-X [PBC] +X [PBC]
-Y [PBC] +Y [PBC]
-Z [APML] +Z [APML]

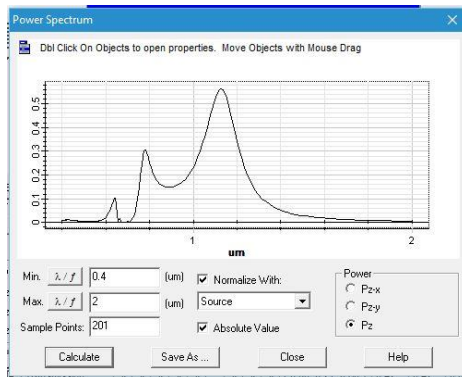
APML Calculation Parameters:

Number of APML Layers [10]
Theoretical Reflection Coefficient [1e-012]
Real APML Tensor Parameter [5]
Power of the Grading Polynomial [3.5]

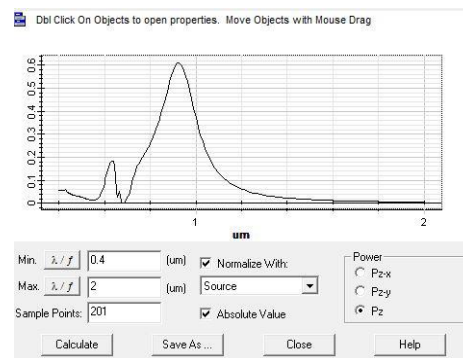
OK Cancel Help

Results

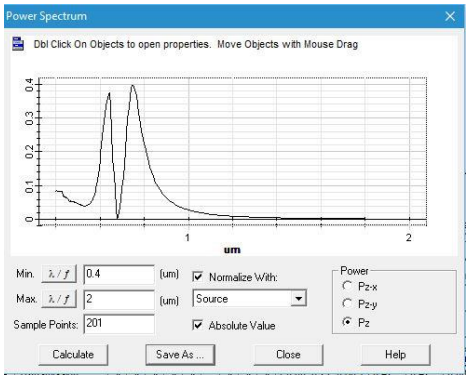
The transmission spectra of the gold-perforated rectangular nano-hole arrays are modified by changing the unequal scaling angle θ . Figure 1 illustrates the transmission spectra of four rectangular nano-hole arrays of various unequal scaling angle ($\theta = 10^\circ, 25^\circ, 45^\circ$, and 55°). During this study, the lattice constant, gold film thickness, substrate refractive index, and orientation angle ϕ toward the x-direction are kept constants at 425 nm, 200 nm, 1.5, and 0° , respectively.



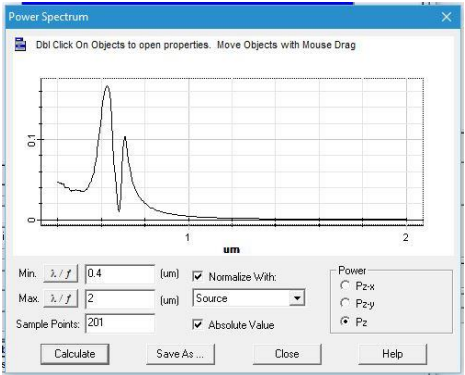
unequal scaling angle (θ) = 10°



unequal scaling angle (θ) = 25°



unequal scaling angle (θ) = 45°



unequal scaling angle (θ) = 55°

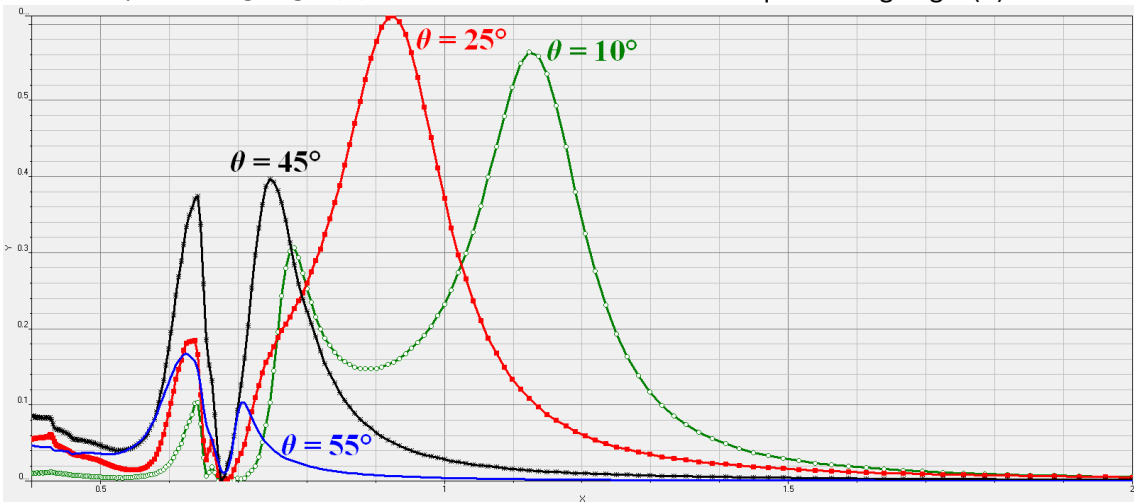
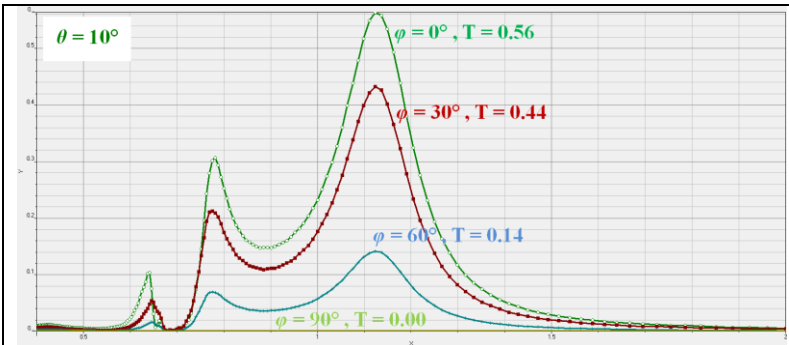


Figure 1: Transmission spectra of gold thin film perforated with rectangular holes at different θ values.

The impact of changing the orientation angle (ϕ) toward the x-direction on the properties of the transmission spectrum is investigated for three aperture arrays of different geometries ($\theta = 10^\circ$, 25° , and 45°). During this study, the lattice constant, gold film thickness, and substrate refractive index are respectively kept constants at 425 nm, 200 nm, and 1.5 and the electric field remains in the y-direction.



Φ	$\theta=10^\circ$		
	$T(\lambda=1.11\mu\text{m})$	$T(\lambda=0.77\mu\text{m})$	$T(\lambda=0.65\mu\text{m})$
0°	0.56	0.31	0.010
30°	0.44	0.21	0.006
60°	0.14	0.07	0.002
90°	0.00	0.00	0.000
120°	0.14	0.07	0.002
150°	0.44	0.21	0.006
180°	0.56	0.31	0.010

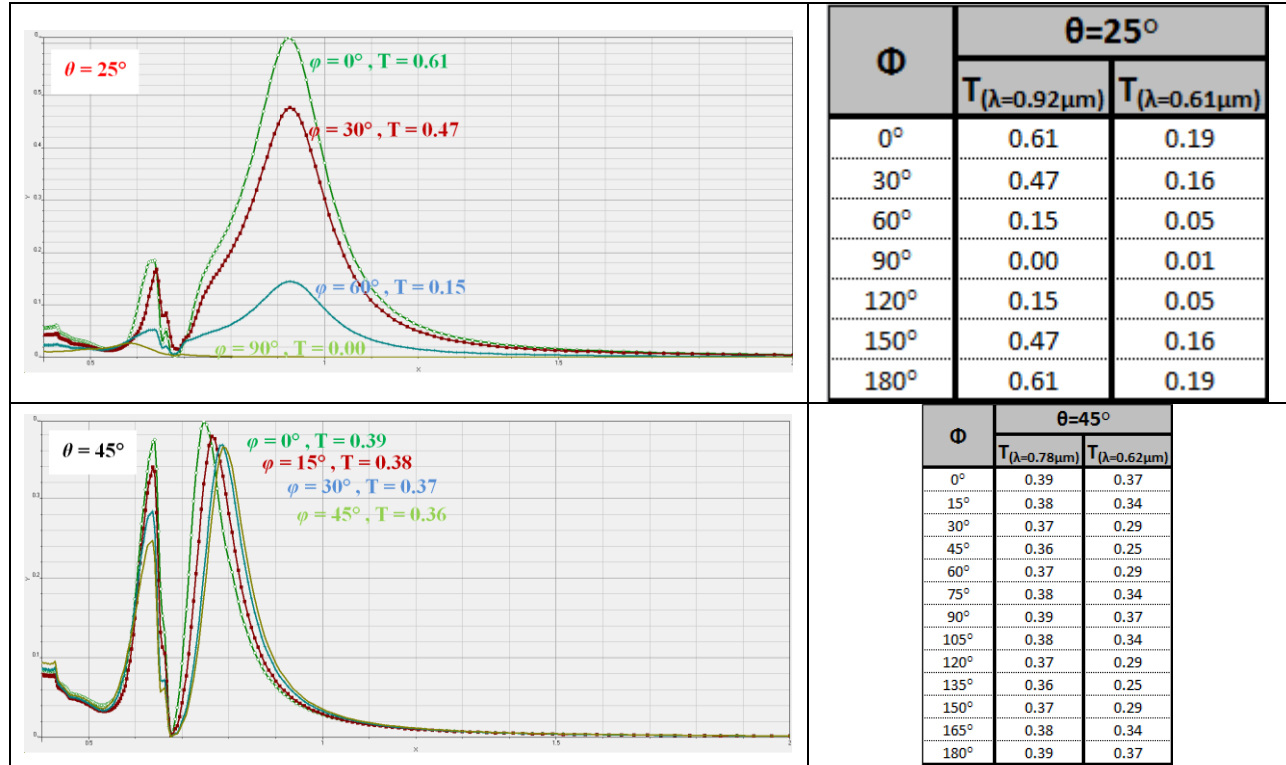


Figure 2: Transmission spectra of gold thin film perforated with rectangular holes at different Φ values.

Using the results shown in Figure 2,

1. One can conclude that the amplitudes of the transmission spectra of the asymmetrical rectangle apertures ($\theta = 10^\circ$ and 25°) are strongly modulated by the orientation angle.
2. The transmission intensity shows a 2-fold symmetry around $\Phi = 90^\circ$.

3. Inspired by the polarizer, the peak transmittance T can be expressed as:

$$T_p(\Phi) = k [\cos^2(\Phi - \Phi_0) + \cos(\Phi - \Phi_0) \sin(\Phi - \Phi_0)],$$

where Φ_0 and k are fitting parameters.

4. The intensity of the spectrum of the symmetrical square nano-holes ($\theta = 45^\circ$) at the resonance wavelengths shows less orientation dependencies (almost constant ($\approx 36\% - 39\%$)).

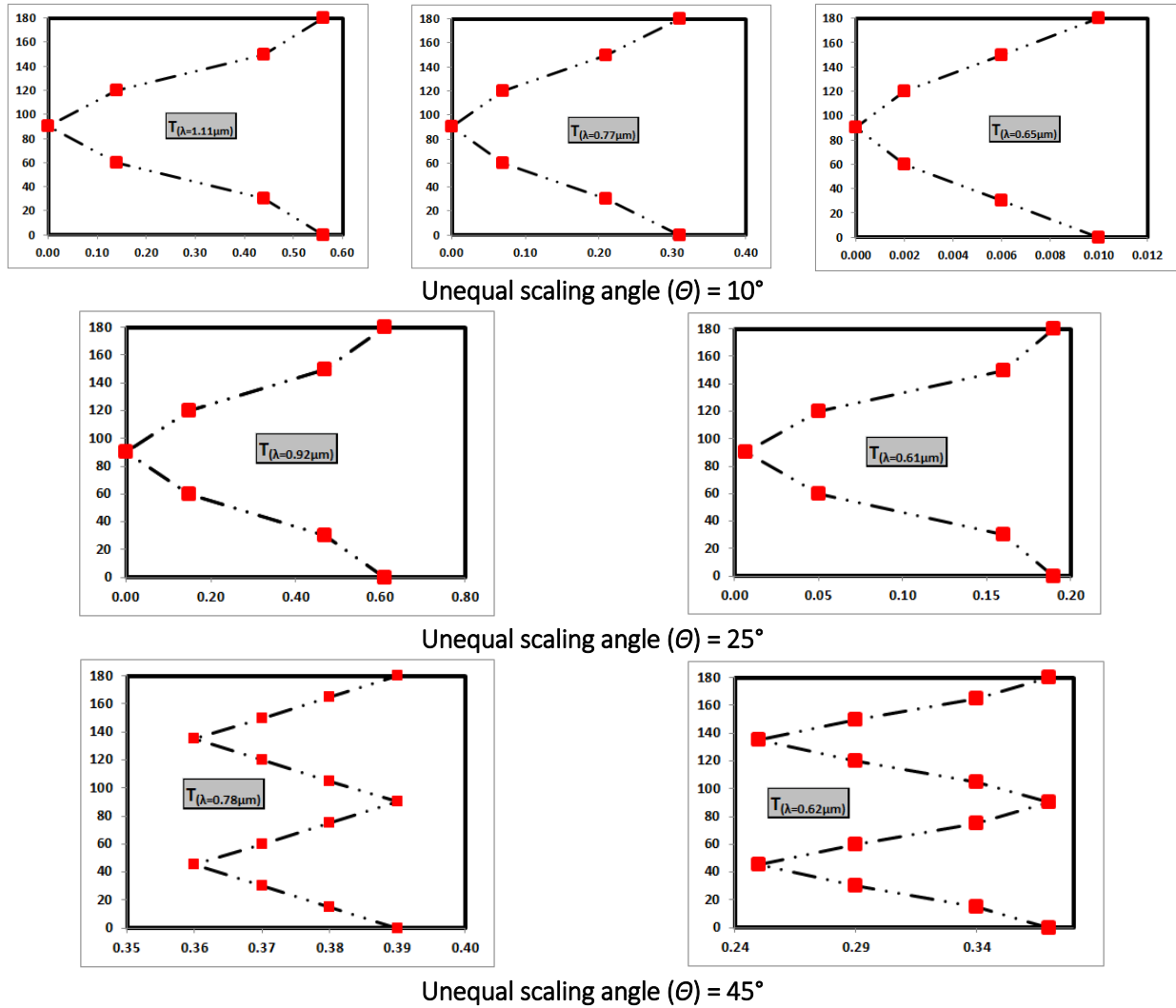


Figure 3: Orientation angle dependencies of transmission peaks intensities at the wavelengths indicated in panels.

References

- [1] Amr M. Mahros, Marwa M. Tharwat, and Islam Ashry, "Exploring the Impact of Rotating Rectangular Plasmonic Nano-hole Arrays on the Transmission Spectra and its Application as a Plasmonic Sensor," Journal of the European Optical Society - Rapid publications, vol. 10, Article ID 15023, 6pages, 2015.