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]

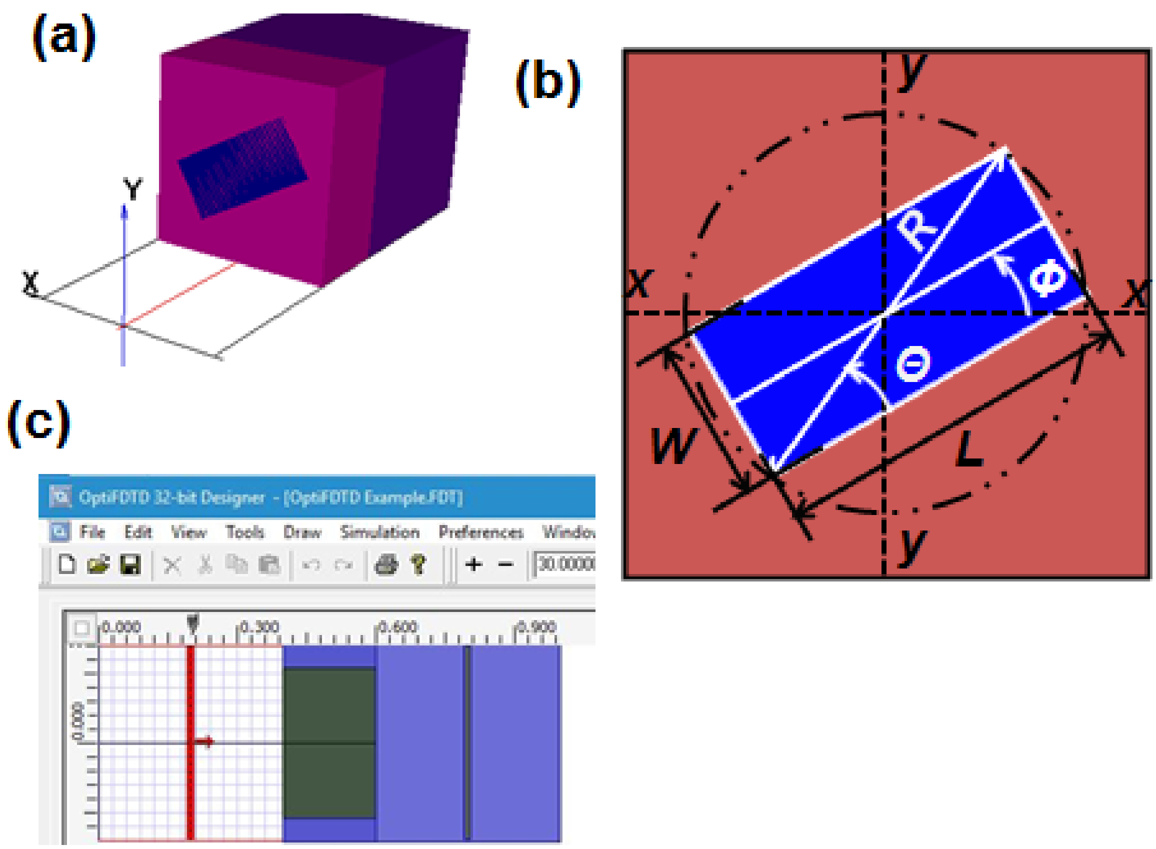
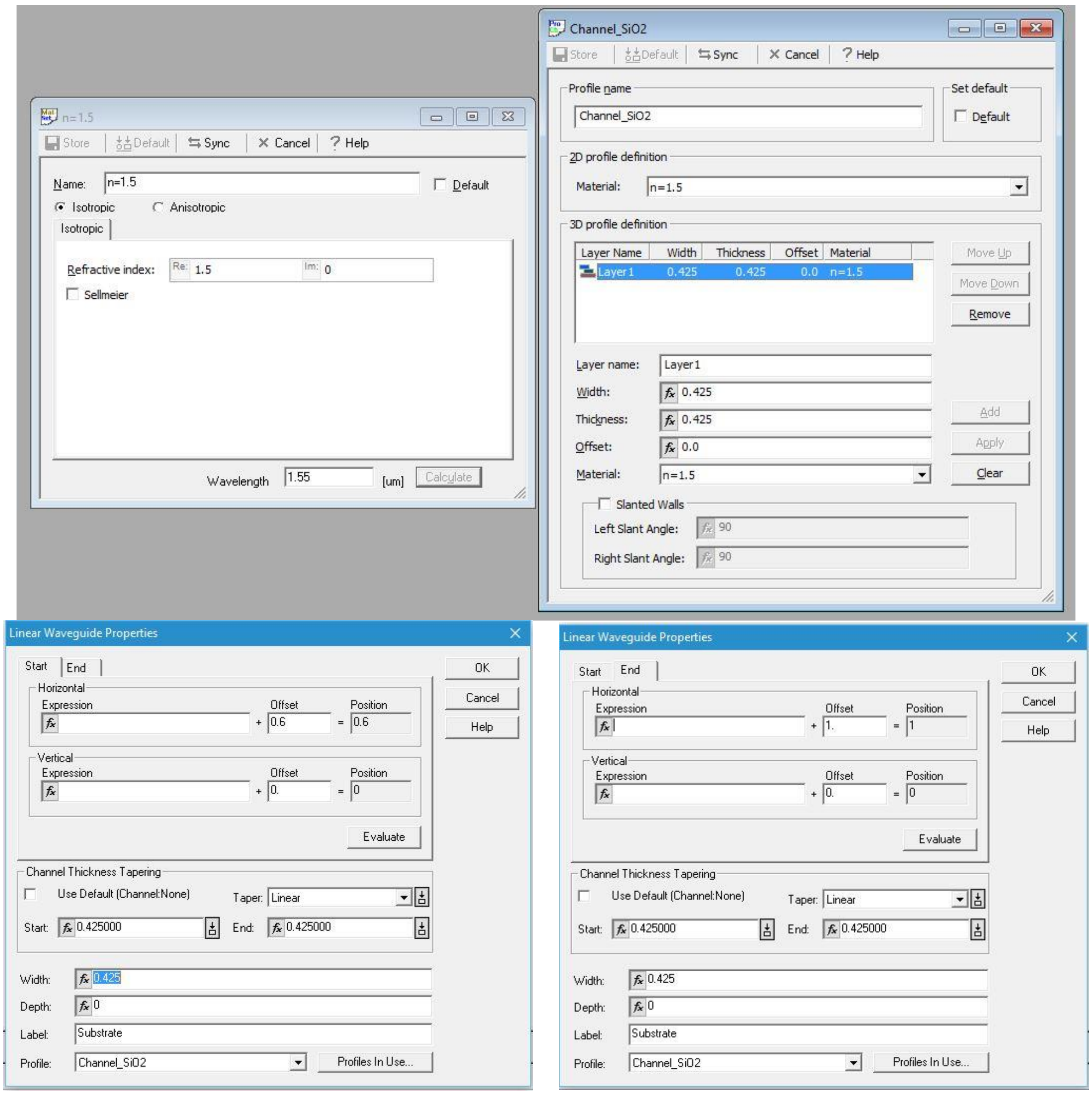



*Figure 1: (a) OptiFDTD single cell 3D layout model, (b) A cross section plan view through the rotatable nano-hole, and (c) OptiFDTD layout of the single cell.*

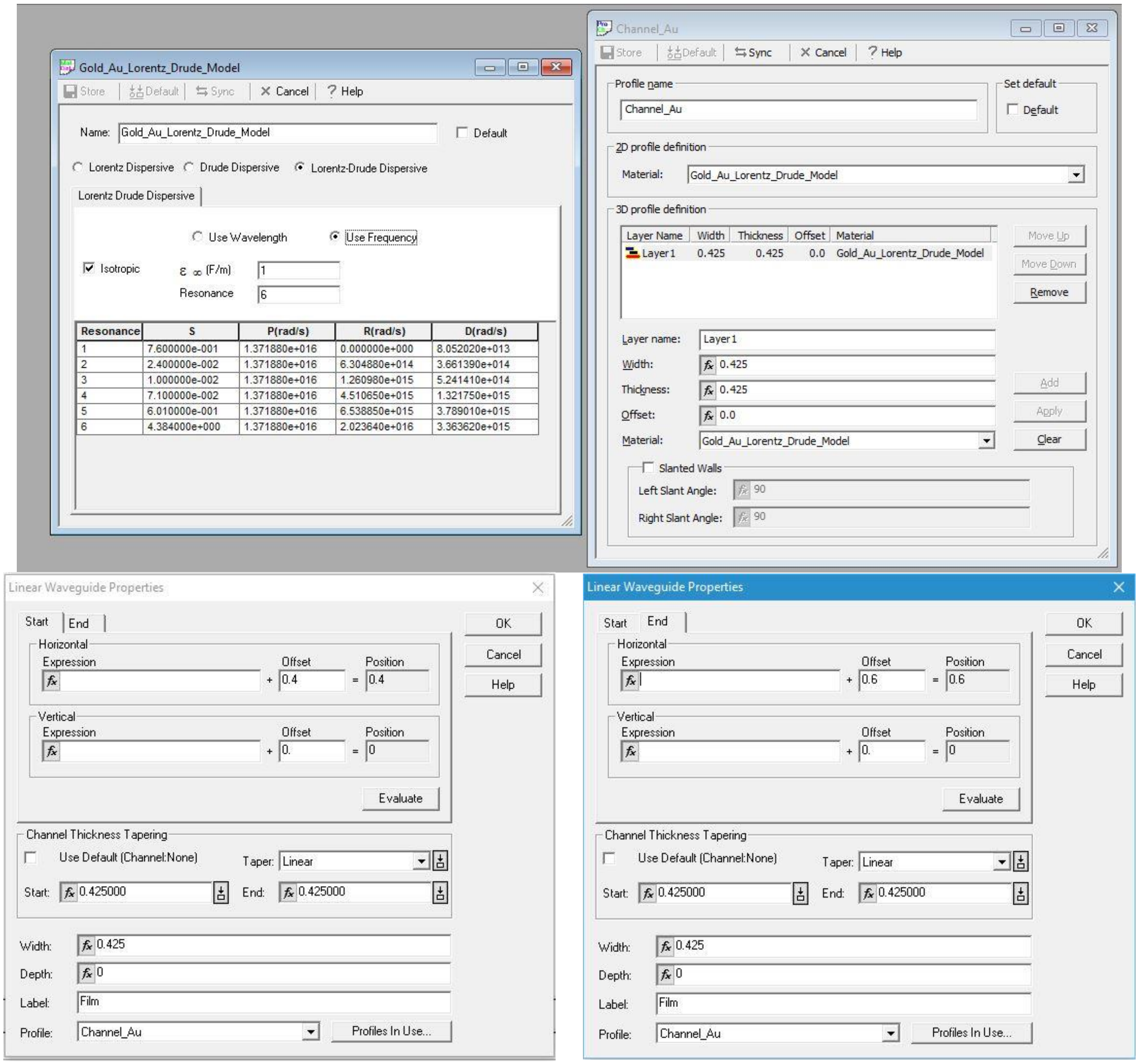
# Project Layout

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**



## 2. The gold Film

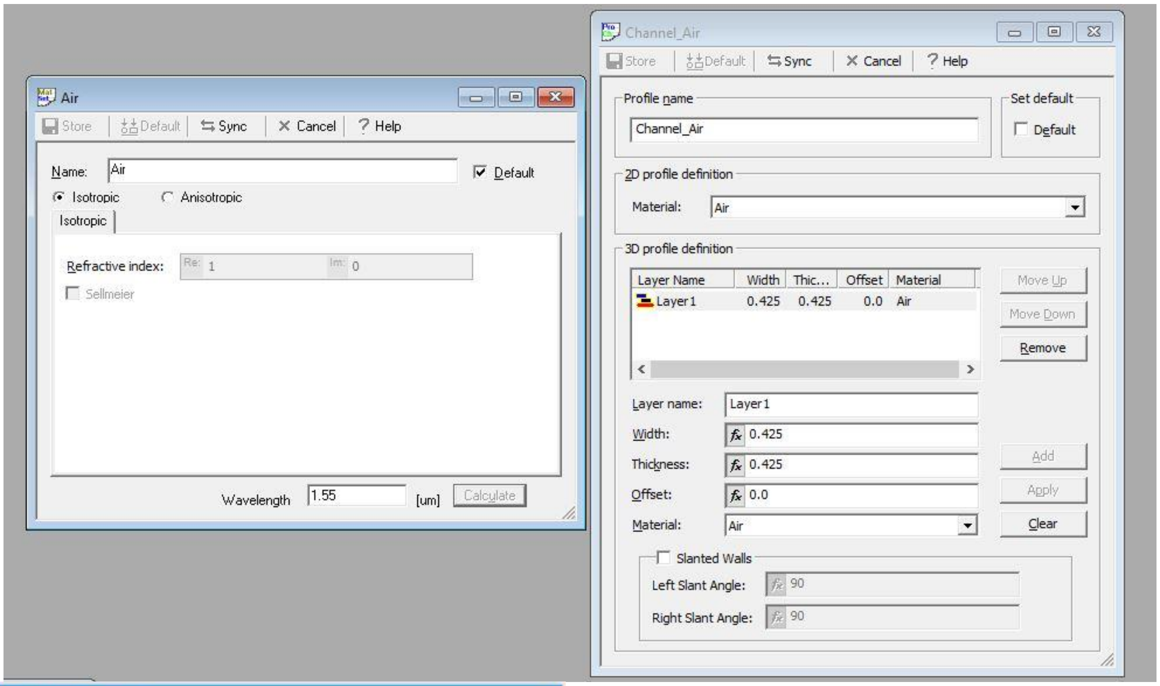


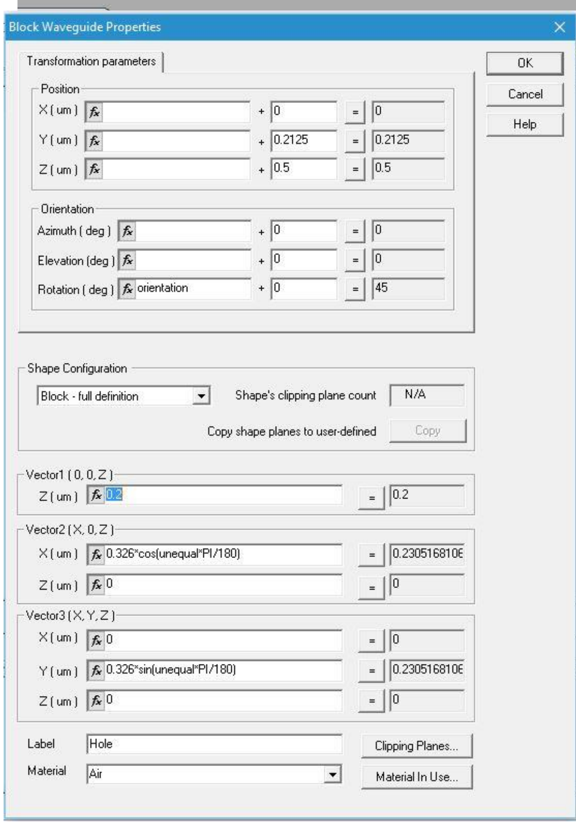

## 3. The nano-holes

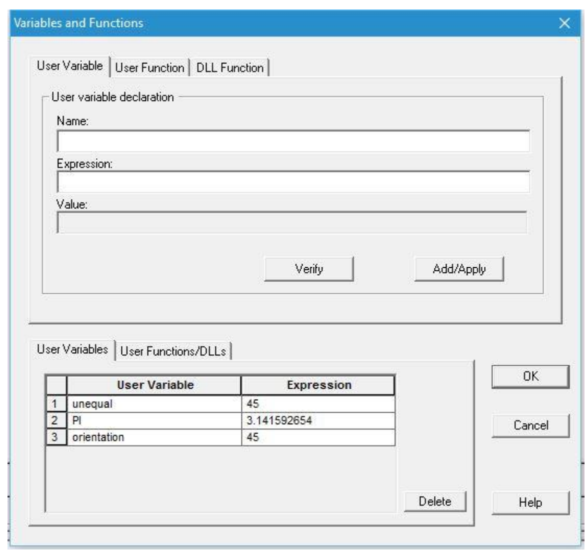
The nano-holes have a rectangular shape and inscribed in identical circles of 326 nm diameter ($D$). The structural periodicity is 425 nm and the gold film thickness is 200 nm. Dimensions of the rectangle structures are determined by unequal scaling angle (θ) and the radius of the reference circular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

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

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


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
Layer1
0.425
0.425
0.0
Air
Move Up
Move Down
Remove
Layer name:
Layer1
Width:
0.425
Thickness:
0.425
Offset:
0.0
Material:
Air
Add
Apply
Clear
Slanted Walls
Left Slant Angle:
90
Right Slant Angle:
90


Block Waveguide Properties
Transformation parameters
OK
Cancel
Help
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
+ 0
= 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)
= 0.2305168106
Z ( um )
0
= 0
Vector3 ( X, Y, Z )
X ( um )
0
= 0
Y ( um )
0.326*sin(unequal*PI/180)
= 0.2305168106
Z ( um )
0
= 0
Label
Hole
Clipping Planes...
Material
Air
Material In Use...

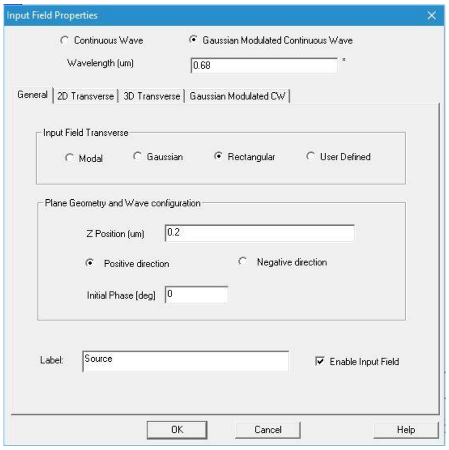

Variables and Functions
User Variable
User Function
DLL Function
User variable declaration
Name:
Expression:
Value:
Verify
Add/Apply
User Variables
User Functions/DLLs
User Variable
Expression
1 unequal 45
2 PI 3.141592654
3 orientation 45
OK
Cancel
Delete
Help

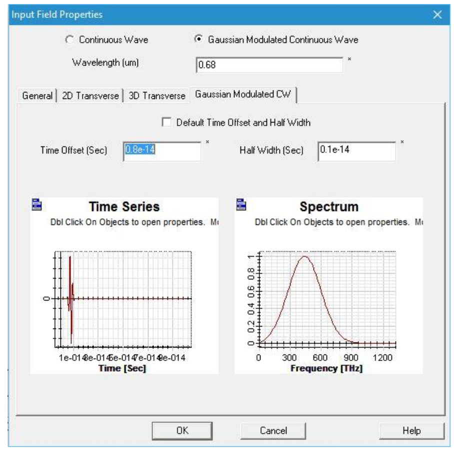
**Design VB script code to scan the unequal scaling and orientation angles**

```
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**

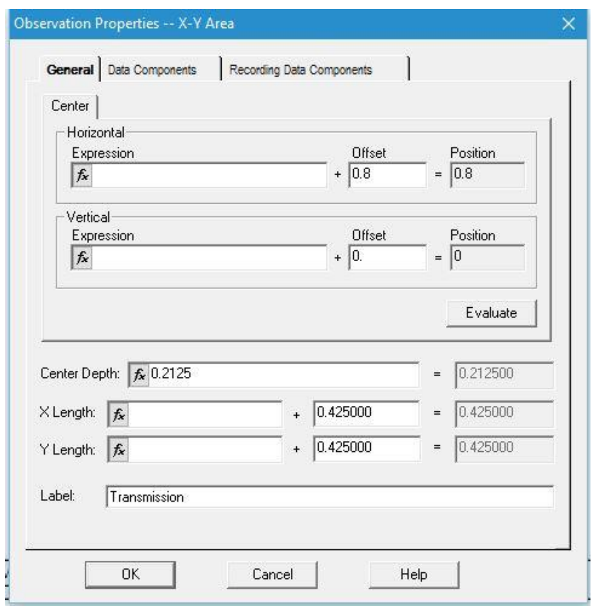
In order to realize a broadband simulation on the dispersive gold film, Gaussian modulated electromagnetic plane wave source was used. The continuous waves are centered at 680 nm, linearly polarized in *y*-direction, and convoluted with a Gaussian envelope function. In the time domain, the light pulse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



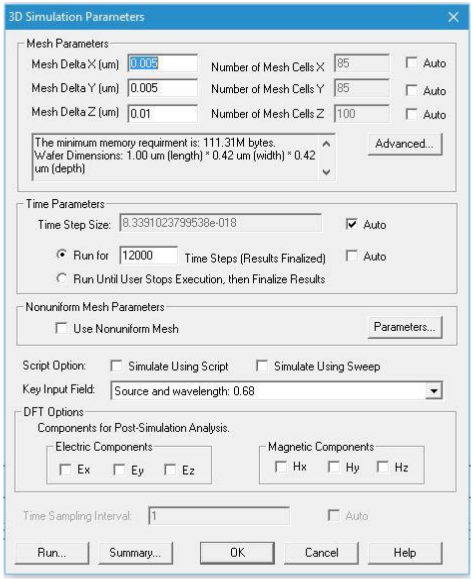

## Define observation area

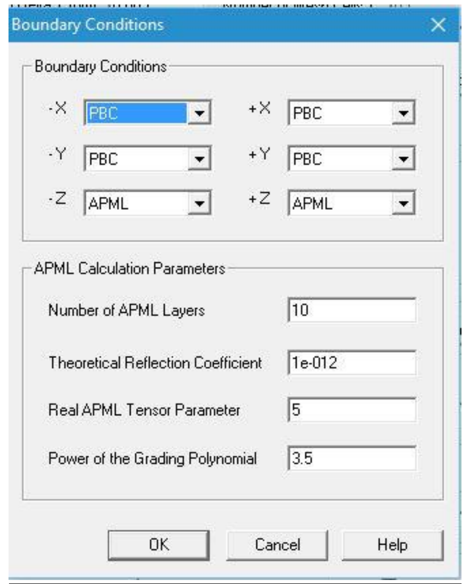
An observation area will perform and calculate the transmission spectral analysis at 400 nm away from the air/Au film interface.




## Simulation parameters and boundary conditions

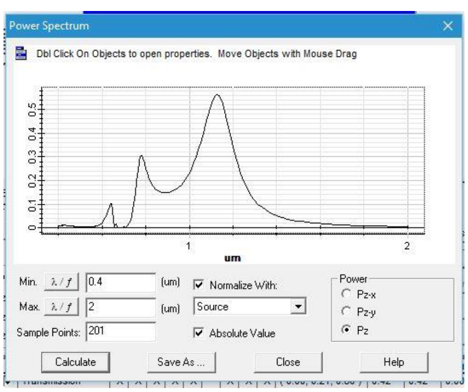
The simulation cell is 425 nm × 425 nm × 1000 nm in the Cartesian coordinates x, y, and z. An absorbing boundary condition was rendered in the z-direction using anisotropic perfect matching layer, while, periodic boundary conditions were used in the x and y directions. The mesh size is adjusted to be 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 λ) to get accurate results. The simulation is executed through 12,000 time step for a calculation time of 100 fs.



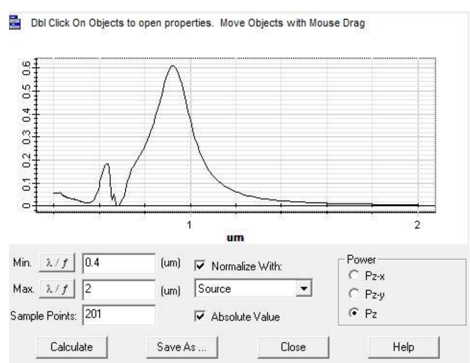




# Results

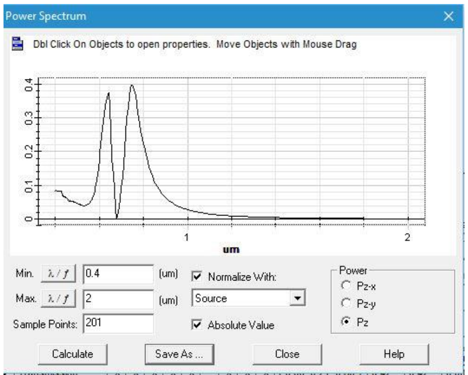
The transmission spectra of the gold-perforated rectangular nano-hole arrays are modified by changing the unequal scaling angle *Θ*. Figure 1 illustrates the transmission spectra of four rectangular nano-hole arrays of various unequal scaling angle (*Θ* = 10°, 25°, 45°, and 55°). During this study, the 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.



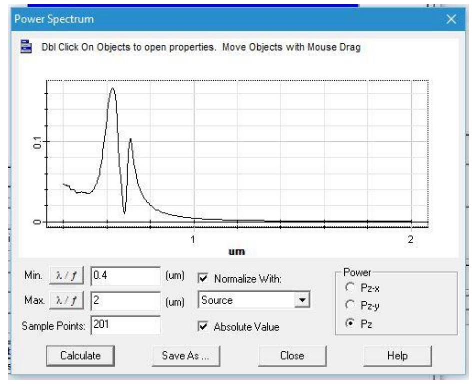

unequal scaling angle (*Θ*) = 10°




unequal scaling angle (*Θ*) = 25°




unequal scaling angle (θ) = 45°




unequal scaling angle (θ) = 55°

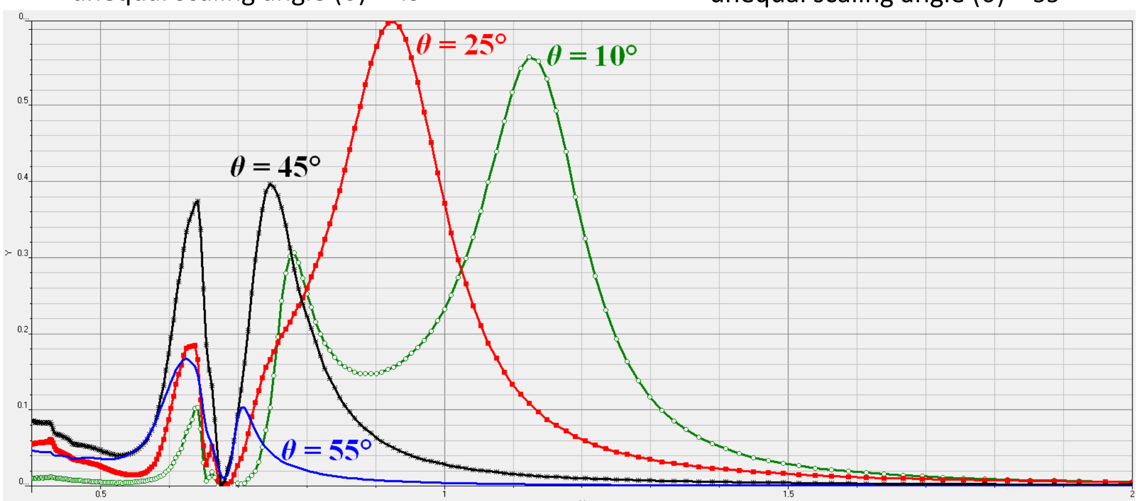
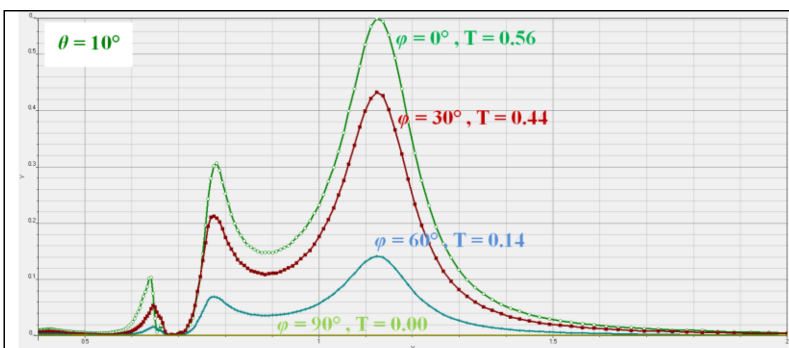
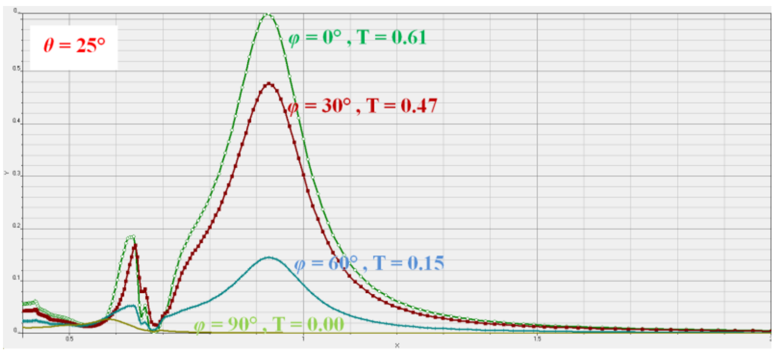



*Figure 1: Transmission spectra of gold thin film perforated with rectangular holes at different Θ values.*

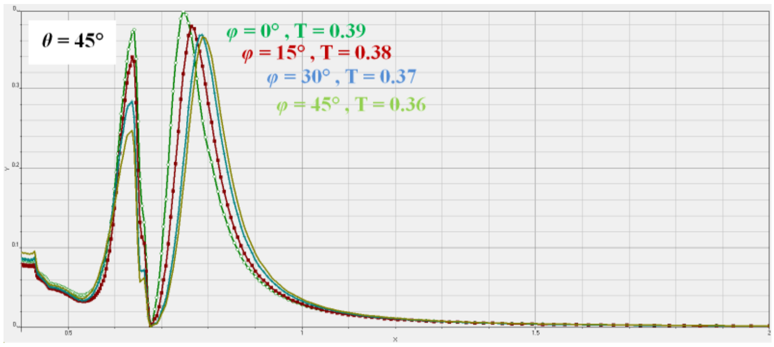
The impact of changing the orientation angle (*Φ*) toward the *x*-direction on the properties of the transmission spectrum is investigated for three aperture arrays of different geometries (*Θ* = 10°, 25°, and 45°). During this study, the lattice constant, gold film thickness, and substrate refractive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




| Φ | θ=10° | | |
|---|---|---|---|
| | $T_{(\lambda=1.11\mu m)}$ | $T_{(\lambda=0.77\mu m)}$ | $T_{(\lambda=0.65\mu m)}$ |
| 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 |




| Φ | θ=25° | |
|---|---|---|
| | T(λ=0.92µm) | T(λ=0.61µm) |
| 0° | 0.61 | 0.19 |
| 30° | 0.47 | 0.16 |
| 60° | 0.15 | 0.05 |
| 90° | 0.00 | 0.01 |
| 120° | 0.15 | 0.05 |
| 150° | 0.47 | 0.16 |
| 180° | 0.61 | 0.19 |




| Φ | θ=45° | |
|---|---|---|
| | T(λ=0.78µm) | T(λ=0.62µm) |
| 0° | 0.39 | 0.37 |
| 15° | 0.38 | 0.34 |
| 30° | 0.37 | 0.29 |
| 45° | 0.36 | 0.25 |
| 60° | 0.37 | 0.29 |
| 75° | 0.38 | 0.34 |
| 90° | 0.39 | 0.37 |
| 105° | 0.38 | 0.34 |
| 120° | 0.37 | 0.29 |
| 135° | 0.36 | 0.25 |
| 150° | 0.37 | 0.29 |
| 165° | 0.38 | 0.34 |
| 180° | 0.39 | 0.37 |

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

Using the results shown in Figure 2,

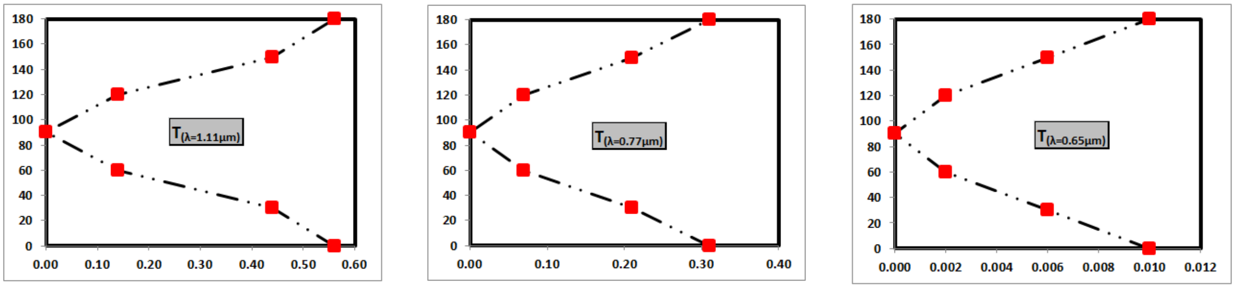
1. One can conclude that the amplitudes of the transmission spectra of the asymmetrical rectangle apertures (Θ = 10° and 25°) are strongly modulated by the orientation angle.
2. The transmission intensity shows a 2-fold symmetry around Φ = 90°.

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

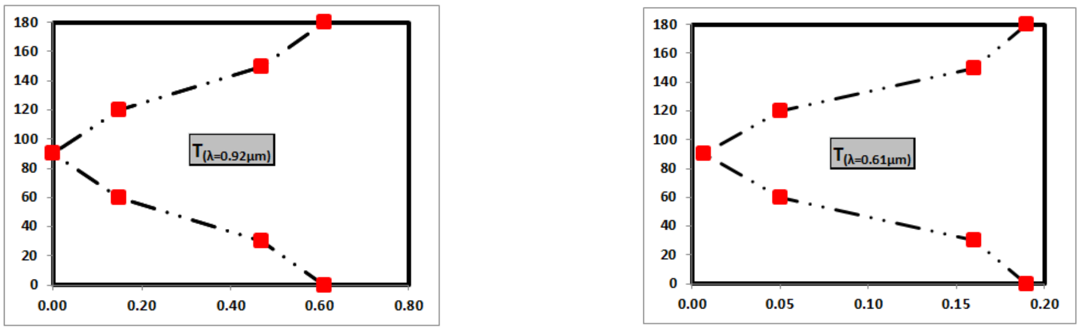
$$T_p(\Phi) = k\,[\cos^2(\Phi - \Phi_o) + \cos(\Phi - \Phi_o)\sin(\Phi - \Phi_o)],$$

where $\Phi_o$ and $k$ are fitting parameters.

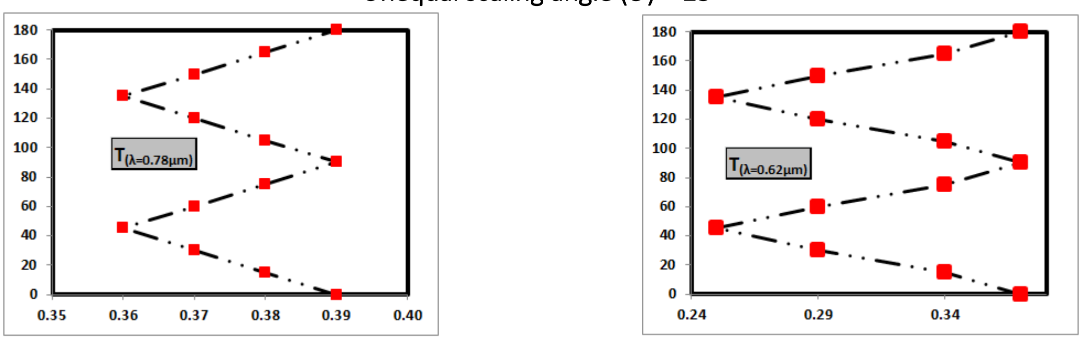
4. The intensity of the spectrum of the symmetrical square nano-holes (Θ = 45°) at the resonance wavelengths shows less orientation dependencies (almost constant (≈ 36 % – 39 %)).




Unequal scaling angle (Θ) = 10°




Unequal scaling angle (Θ) = 25°




Unequal scaling angle (Θ) = 45°

*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.