

# Enhancement of Light Absorption in Plasmonic Based Photodetector with Double Nanograting Structure

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## Research Article

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# Abstract

This era of high speed photonic system demand photodetectors to have large bandwidth, gain and improved light enhancement competence. Amongst the different light absorption enhancement methods being researched by the investigators, plasmonic has acquired increased attention in the last decades. Although single layer plasmonic supported metal semiconductor metal photodetector (MSM-PD) has been explored for higher light absorption efficiency, but exploration for double-layer structure is lacking in the literature. This paper presents the performance of plasmonic based photodetectors (PDs) with double layer of nanogratings optimized at wavelength of  $1.4 \mu\text{m}$  for night vision applications. Proposed design of plasmonic supported photodetector with double nanograting reports Quenching factor (QF) of 92.14% and provides enhancement in light with the optimized height of subwavelength aperture (SWA) at 60 nm. This can be credited to fact that both top and bottom layer of grating contributes to light trapping.

## 1. Introduction

The modern era has observed an extensive concern of researchers for the expansion of nano-scale, high speed photonic devices [1]. Various models of photodetectors (PDs) have been explored by researchers for high bandwidth, gain and improved light enhancement capability. Plasmonic based metal semiconductor metal photodetectors (MSM-PDs) have been accepted as a promising contender for high speed photonic devices [2–4] and it has significant role for future-generation optoelectronic devices for high speed. In recent years, role of Surface Plasmons (SPs) in the plasmonic field has become a major research topic that contributes the maximum output depending on the incident light. These are the oscillations of electron cloud present on the metal surface results in light confinement and light enhancement [5–7]. Various Plasmonic based PDs has been analyzed with a single layer of diverse groove with shapes viz. trapezoidal, rectangular, elliptical and triangular at wavelengths 986 nm and 827 nm [8–10]. Researchers have been proposed different nano structured MSM-PD models and compute the light absorption enhancement factor (LAEF) by changing the geometric properties of the device [11, 12]. Most of the existing designs focus on the use of noble metal like gold (Au) with single layer of nanogratings on the metal surface [13]. These structures suffer with drawback of large amount back reflections of light. From literature, *Tan et al.* [1] have reported 1.5 LAEF with single nanogratings based plasmonic PD using gold material. *Tan et al.* [14] have presented 1.2 LAEF with double gratings based photodetector using gold material at 900 nm top first grating width and also proposed the high absorption device by embedding metal nanoparticles with nanogratings [15]. *Masouleh et al.* [16] have obtained 1.56 LAEF at  $1.4 \mu\text{m}$  using gold material for nanogratings with 450 nm SWA width and also compared the different plasmonic nanogratings profile to enhance the light absorption in nanostructured device [17]. *Daneshmandi et al.* [18] have proposed extra ordinary transmission (EOT) structure based photodetector to improve the light transmission within the device whereas, *Das et al.* [19] have analyzed the effect of nanogratings phase-shift on device performance and examined that maximum device performance has been achieved at  $0^\circ$  but it start decreases by increasing the phase-shift beyond  $0^\circ$ . *Fan et al.* [20] have reported the plasmonic based MSM-PD with aluminum nanogratings and also obtained

the light reflection factor (LRF). [21] Though the research community has provided numerous solutions for improving the device performance yet, MSM-PD devices suffer from reflection losses. Therefore, literature demands investigation of plasmonic supported MSM-PD with additional noble metals viz. silver. Improvisation of plasmonic supported MSM-PD structure with double layer of nanogratings for superior light absorption lacks in literature. This paper presents the plasmonic based PD with double nanogratings structure to enhance the light absorption. Proposed structure adds a bottom layer of metal gratings along with top metal gratings and SWA using silver as a cost effective alternative to gold. With the help of SWA light can not be dispersive in all angles [16] and it helps to re-emit the light from a very small area occupied by the SWA. The order of the paper as follows: Section I, i.e., "Introduction" is followed by Section II that describes the "structural design of the proposed double nanogratings layer based PD". Results obtained from the research work with all justifications are presented in Section III. Finally, the "Conclusions" derived from research work are described in Section IV.

## 2. Photodetector Structure Design

This section describes the double nanograting structure of the proposed plasmonic based PD as shown in Fig. 1 which consists four parts i.e. top grating, SWA, bottom grating and substrate. This novel structure design is the advancement of the single grating structure to maximize the light absorption and reduce the light reflection. Initially, light is incident on the top metal gratings and coupled to top layer where it transmitted with surface plasmon by SWA. As incoming light hit the metal top surface, it induces electrons oscillations in the figure of surface plasmon with the help of metal-free electrons. With the help of these oscillations light is coupled with the bottom nanogratings and absorb in the substrate and generate electron-hole pairs within the substrate leads to light absorption enhancement. Proposed design uses silver (Ag) material for nanogratings, SWA and gallium arsenide (GaAs) as substrate whereas plasmonic supported PD is simulated using OptiFDTD software based on the Drude model [22].

For the better absorption, GaAs is mainly preferred over other semiconductor materials. Because of its better electrical properties and wide direct band gap (1.42 eV) for more light absorption and it also attained high responsivity due to high electron mobility. Noble material i.e., silver is used because it has less ohmic losses, stable in the environment, best conductor of heat and it is suitable for plasmons as compared to other materials. This work uses (finite difference time domain) FDTD based algorithm for the study of optical properties of nanostructures [23] and simulations of the electromagnetic field component. For the FDTD simulation, mesh size used is 5 nm and permittivity for GaAs is assumed to be real and taken from [24]. A periodic boundary condition along x direction, anisotropic perfectly matched layer (APML) in z direction is supposed for the simulations and structure consists of parallel grooves in x-direction made from perfect conductors.

## 3. Results And Discussion

In this section, the performance of plasmonic based PD has been analyzed, whereas the impact of SWA height at 40 nm, 60 nm and 80 nm has been studied and analyzed accordingly. Simulated refractive

index plot, distribution of magnetic field in x ( $H_x$ ) and z direction ( $H_z$ ) have been attained and depicted in Figs. 2–3, respectively. Vertical plane kept at position 0.125 is used for the input light and incoming light used which lies in near-infrared region from range 1.1  $\mu\text{m}$ - 1.55  $\mu\text{m}$  with TM mode and  $\theta = 0^\circ$ . In this research work, we have obtained the LAEF by varying SWA height of values 40 nm, 60 nm and 80 nm and keeping SWA width constant at 50 nm. The term LAEF demonstrates the effect of nanogratings for light transmitted within the substrate through a coupling process based on resonance phenomenon. Table. 1 presents all the parameters for proposed double nanograting supported PD having rectangular grooves in the NIR region.

When the light is traversing with surface plasmon resonance the bottom layer prevents the loss by trapping the light using nano-gratings and thus increases absorption and bottom gratings further distribute the light in wider area of substrate. However, resonance occurs only when the frequencies of incoming light and electron cloud oscillations that are present on the surface matches with each other. With the coupling effect, light is automatically absorbed when the surface plasmon resonance happens.

**Table 1**

Parameters for double grating layer structure

Parameters	Values
Groove shape	Rectangular
Input wavelength	1.1 $\mu\text{m}$ – 1.55 $\mu\text{m}$
Top Gratings height	60 nm
SWA width	50 nm
Bottom gratings height	40 nm
SWA height	(40, 60, 80) nm
Bottom gratings and Substrate material	GaAs
Number of gratings	4
Top gratings and SWA material	Silver

Refractive index layout with double nanograting structure design is shown in Fig. 2. However, top and bottom gratings enhance the light with SPPs due to excitation of SPPs with the interaction of light with the metal in nanostructures. Due to change in the refractive index, nanostructures help in increase the light transmission which passes through the SWA [25] whereas, Fig. 3 (a) and 3 (b) presents magnetic field (H) along x and z axis. It is clearly noticed from Fig. 3 (a-b) that bottom grating distributes the maximum light within the substrate because of the light coupling process. If light transmission with double nanogratings through SWA increases then light absorption within the GaAs substrate also increases due to resonance phenomenon. So, the nanogratings are acting as plasmonic lenses or light

concentrators [26] which is essential for triggering extraordinary optical absorption (EOA) of light into the substrate. For analyzing the design two performance metrics used includes QF and LAEF. LAEF, “the ratio of normalized power transmittance with double nanogratings to normalized power transmittance without top nanogratings” is calculated using Eq. (1) [27] whereas, QF describes the enhancement in light absorption from least amount to upper limit is calculated using Eq. (2) [28].

$$LAEF = \frac{\text{Normalized Power transmittance with double nanogratings}}{\text{Normalized Power transmittance without top nanogratings}} \quad (1)$$

$$QF = \frac{\text{Maximum LAEF} - \text{Minimum LAEF}}{\text{Maximum LAEF}} \quad (2)$$

From the simulated results, Fig. 4 represents the LAEF spectra with variation in SWA height at a constant width of 50 nm. From results, we have obtained that optimized height of top and bottom nanogratings are 60 nm and 40 nm at which we achieved the maximum light absorption with highest QF by doing variations in the SWA height.

Table 2 summarizes the performance parameters with maximum QF and LAEF over different heights of SWA at 1.4  $\mu\text{m}$ . Hence from the simulated results, it is depicted that maximum LAEF of 2.2435 is achieved at optimized SWA height is 60 nm as compared to other heights in the presence of SPPs. It is concluded from 92.14 % QF that highest light enhancement is observed with SWA height of 60 nm for the proposed design as mentioned in Table 2. This can be credited from the fact that enhancement of light absorption depends on surface plasmon resonance and in double nanograting based photodetector both top and bottom layer contributes to enhanced light trapping. It is observed that light absorption highly depends upon nanogratings height and material. Proposed design because better results have vital role in night vision applications and can be utilized for future generation opto-electronic system. In the future this structure can be analyzed with other groove shapes for both top and bottom gratings to enhance light trapping further.

**Table 2**

Maximum LAEF with quenching factor (QF) at 1.4  $\mu\text{m}$  input wavelength

Parameters	Values	
Input wavelength for maximum LAEF	1.4 $\mu\text{m}$	
SWA height (nm)	Maximum LAEF	QF (%)
80	0.8	25
60	2.2435	92.14
40	0.99	89.89

## 4. Conclusion

Single layer plasmonic based photodetector needs more exploration for light absorption enhancement. Paper presents plasmonic based photodetector by adding one more grating of rectangular grooves and analyses the LAEF for a structure and design has been analyzed over varying SWA heights i.e., 40 nm, 60 nm and 80 nm keeping other parameters constant. Maximum LAEF is 2.2435 leading to QF of 92.14% has been achieved with SWA optimized height of 60 nm at 1.4  $\mu\text{m}$  making it suitable for applications in night vision. It is interesting to note that the parameters of both top and bottom gratings are different from each other. But bottom metal gratings enhance the maximum light as compared to single grating structure. This can be credited to the fact that the bottom grating is minimizing light reflection and enhancing light trapping due to the nanogratings.

## **Declarations**

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### **Conflict of Interest/ competing interest**

The authors declare that they have no conflict of interest.

### **Availability of data and material**

The authors declare that data supporting the findings of this study are available within the article.

### **Code availability**

Not applicable

### **Authors' contributions**

Designing, Methodology, Data and Result Analysis, Writing-original draft preparation: Savita Kashyap; Manuscript review, Editing and Supervision: Harsimranjit Kaur

### **Ethics approval**

Not Applicable

### **Consent to participate**

Informed consent was obtained from all individual participants included in the study.

### **Consent for publication**

Not Applicable

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## References

1. Tan CL, Lysak VV, Alameh K, Lee Y T (2010) Absorption enhancement of 980 nm MSM photodetector with a plasmonic grating structure. *Opt Commun* 283:1763-1767
2. White JS, Veronis G, Yu Z, Barnard ES, Chandran A, Fan S, et al (2009) Extraordinary optical absorption through subwavelength slits. *Opt Lett* 34:686-688
3. Chen S, Cao R, Chen X, Wu Q, Zeng Y, Gao S, et al (2020) Anisotropic Plasmonic Nanostructure Induced Polarization Photoresponse for MoS<sub>2</sub>-Based Photodetector. *Adv Mater Interfaces* 7:1902179
4. Li MY, Yu M, Jiang S, Liu S, Liu H, Xu H, et al (2020) Controllable 3D plasmonic nanostructures for high-quantum-efficiency UV photodetectors based on 2D and 0D materials. *Materials Horizons* 7:905-911
5. Kashyap S, Kaur H (2019) Comparative Study of Plasmonics Based Metal-Semiconductor-Metal Photodetector. in 2019 6th International Conference on Signal Processing and Integrated Networks (SPIN) 303-308
6. Kashyap S, Kaur H (2019) Impact of silver nanogratings for enhanced light absorption in plasmonic based photodetector. *Optik* 199:163367
7. Li L, Wang J, Kang L, Liu W, Yu L, Zheng B, et al (2020) Monolithic Full-Stokes Near-Infrared Polarimetry with Chiral Plasmonic Metasurface Integrated Graphene–Silicon Photodetector. *ACS Nano* 14:16634-16642
8. Das N, Karar A, Vasiliev M, Tan CL, Alameh K, Lee YT (2010) Groove shape-dependent absorption enhancement of 850 nm MSM photodetectors with nano-gratings. in 10th IEEE International Conference on Nanotechnology 289-293
9. Martin-Moreno L, Garcia-Vidal F, Lezec H, Degiron A, Ebbesen T (2003) Theory of highly directional emission from a single subwavelength aperture surrounded by surface corrugations. *Phys Rev Lett* 90:167401
10. Raether H (1988) Surface plasmons on smooth surfaces. in *Surface plasmons on smooth and rough surfaces and on gratings*, ed: Springer, pp. 4-39.
11. Dhakal D (Analysis of the sub-wavelength grating in OptiFDTD simulator," School of Eng. and Science, Jacobs Univ
12. Shackelford JA, Grote R, Currie M, Spanier JE, Nabet B (2009) Integrated plasmonic lens photodetector. *Appl Phys Lett* 94:083501
13. Das N, Karar A, Vasiliev M, Tan CL, Alameh K, Lee YT (2011) Analysis of nano-grating-assisted light absorption enhancement in metal–semiconductor–metal photodetectors patterned using focused ion-beam lithography," *Opt Commun*, 284:1694-1700

14. Tan CL, Lysak VV, Das N, Karar A, Alameh K, Lee YT (2010) Absorption enhancement of MSM photodetector structure with a plasmonic double grating structure," in 10th IEEE International Conference on Nanotechnology, pp. 849-853.
15. Tan CL, Karar A, Alameh K, Lee YT (2013) Optical absorption enhancement of hybrid-plasmonic-based metal-semiconductor-metal photodetector incorporating metal nanogratings and embedded metal nanoparticles. *Opt Express* 21:1713-1725
16. Masouleh FF, Das N, Mashayekhi HR (2014) Optimization of light transmission efficiency for nano-grating assisted MSM-PDs by varying physical parameters. *Photonics and Nanostructures-Fundam Appl* 12:45-53
17. Masouleh FF, Das NK, Mashayekhi HR (2013) Comparison of different plasmonic nanograting profiles for quality light absorption in nanostructured metal-semiconductor-metal photodetectors. *Opt Eng* 52:127101
18. Daneshmandi O, Sharaf R, Ghayour R (2018) A new high performance MSM hybrid plasmonic photodetector based on nanogratings and dual mode horn shape waveguide. *Nanotechnology* 29:405202
19. Das N, Karar A, Tan CL, Alameh K, Lee YT (2011) Impact of nanograting phase-shift on light absorption enhancement in plasmonics-based metal-semiconductor-metal photodetectors. *Adv Opt Technol* 2011
20. Fan Z, Su Y, Zhang H, Han X, Ren F (2015) Analysis of aluminum nano-gratings assisted light reflection reduction in GaAs metal-semiconductor-metal photodetectors. in *Reliability of Photovoltaic Cells, Modules, Components, and Systems VII* 2015:95630T
21. Bahari A, Salianeh MG (2019) High-Quantum Efficiency of the Plasmonic Photodetectors-Based on Coupling Between Ag Nanoparticles and Ag Nanograting Electrodes. *Plasmonics* 14:415-423
22. Le KQ, Ngo QM, Nguyen TK (2016) Nanostructured metal-insulator-metal metamaterials for refractive index biosensing applications: design, fabrication, and characterization. *IEEE J Sel Top Quantum Electronics* 23:388-393
23. Kikuta H, Toyota H, Yu W (2003) Optical elements with subwavelength structured surfaces. *Opt Rev* 10: 63-73
24. Palik ED (1997) Gallium arsenide (GaAs). in *Handbook of optical constants of solids*, ed: Elsevier, 1997:429-443
25. Ren FF, Ang KW, Song J, Fang Q, Yu M, Lo GQ et al (2010) Surface plasmon enhanced responsivity in a waveguided germanium metal-semiconductor-metal photodetector. *Appl Phys Lett* 97:091102
26. Das N, Islam S (2016) Design and analysis of nano-structured gratings for conversion efficiency improvement in GaAs solar cells. *Energies* 9:690
27. Das N, Masouleh F F, Mashayekhi H R (2012) Nano-structured metal-semiconductor-metal photodetectors for enhanced light absorption. in *2012 5th International Conference on Computers and Devices for Communication (CODEC)* 1-6.

## Figures

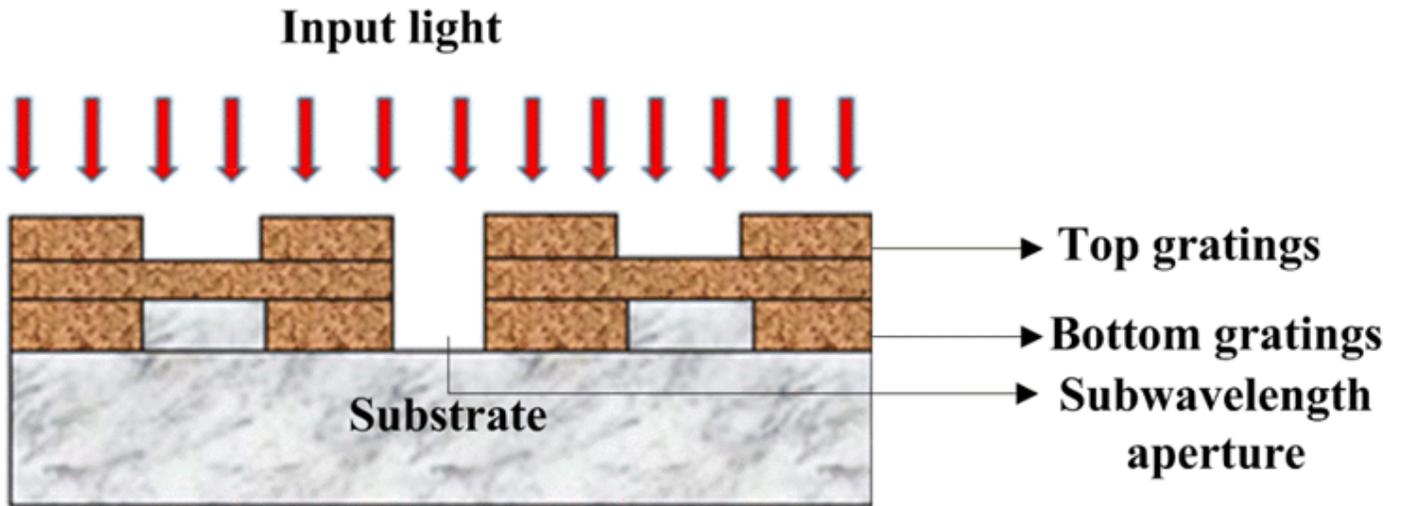


Figure 1

Double layering of nanogratings (top and bottom) based plasmonic photodetector with SWA

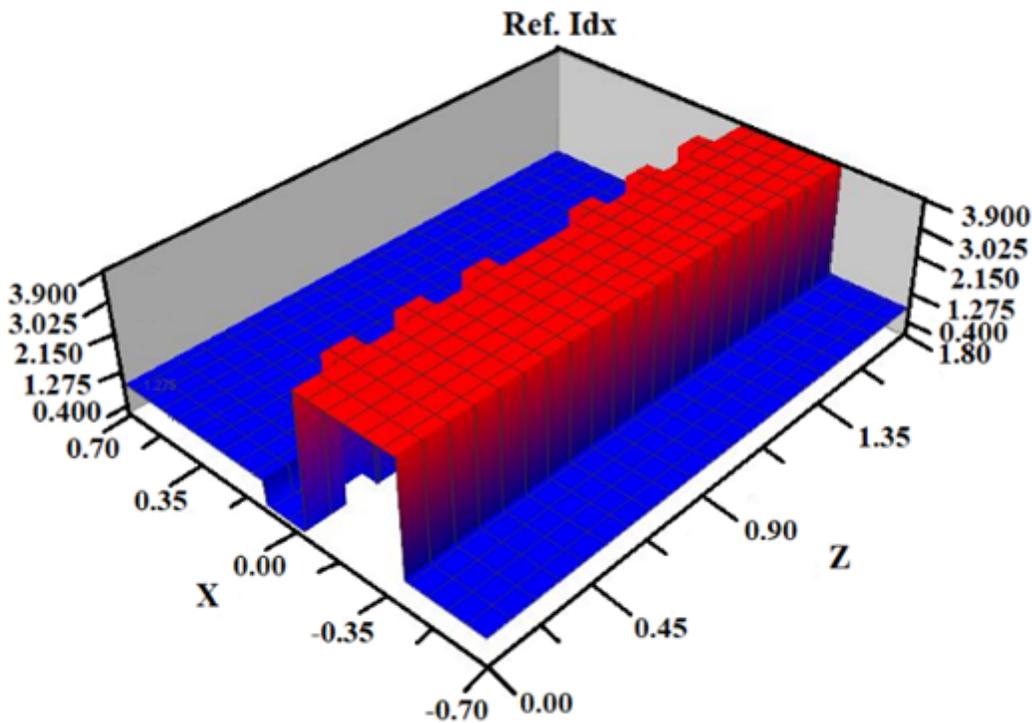
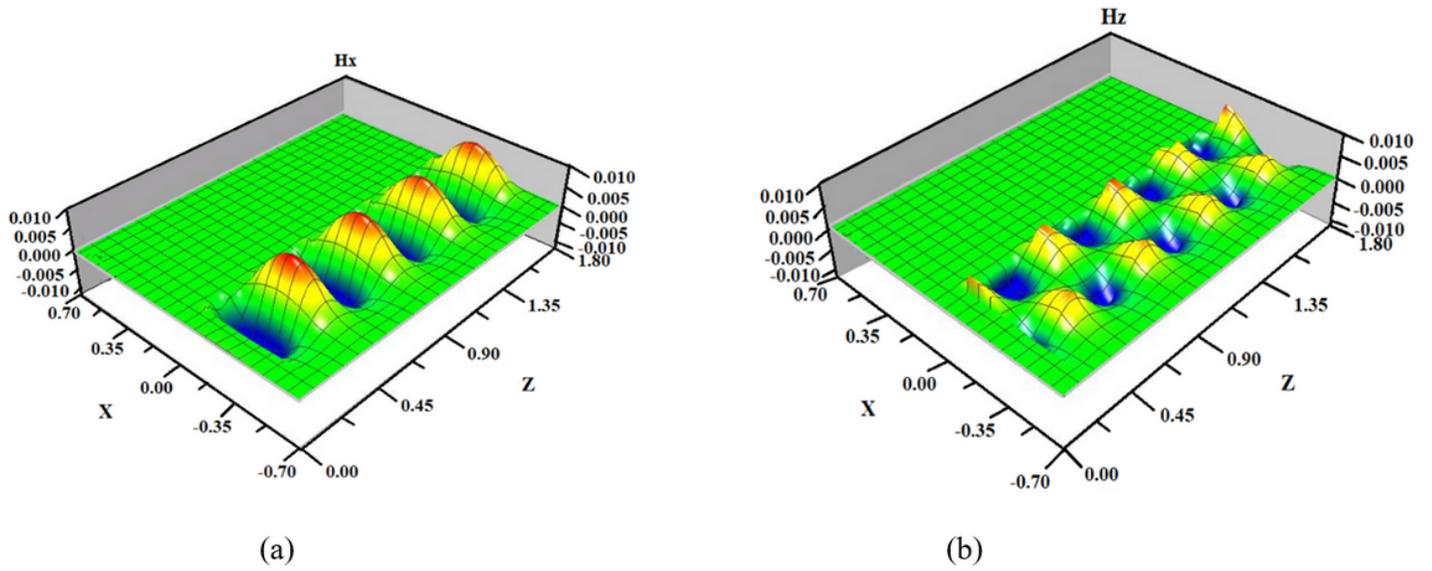


Figure 2



**Figure 3**

(a) Distribution of magnetic field in x direction ( $H_x$ ) (b) in z direction ( $H_z$ ) with rectangular groove shape of silver material

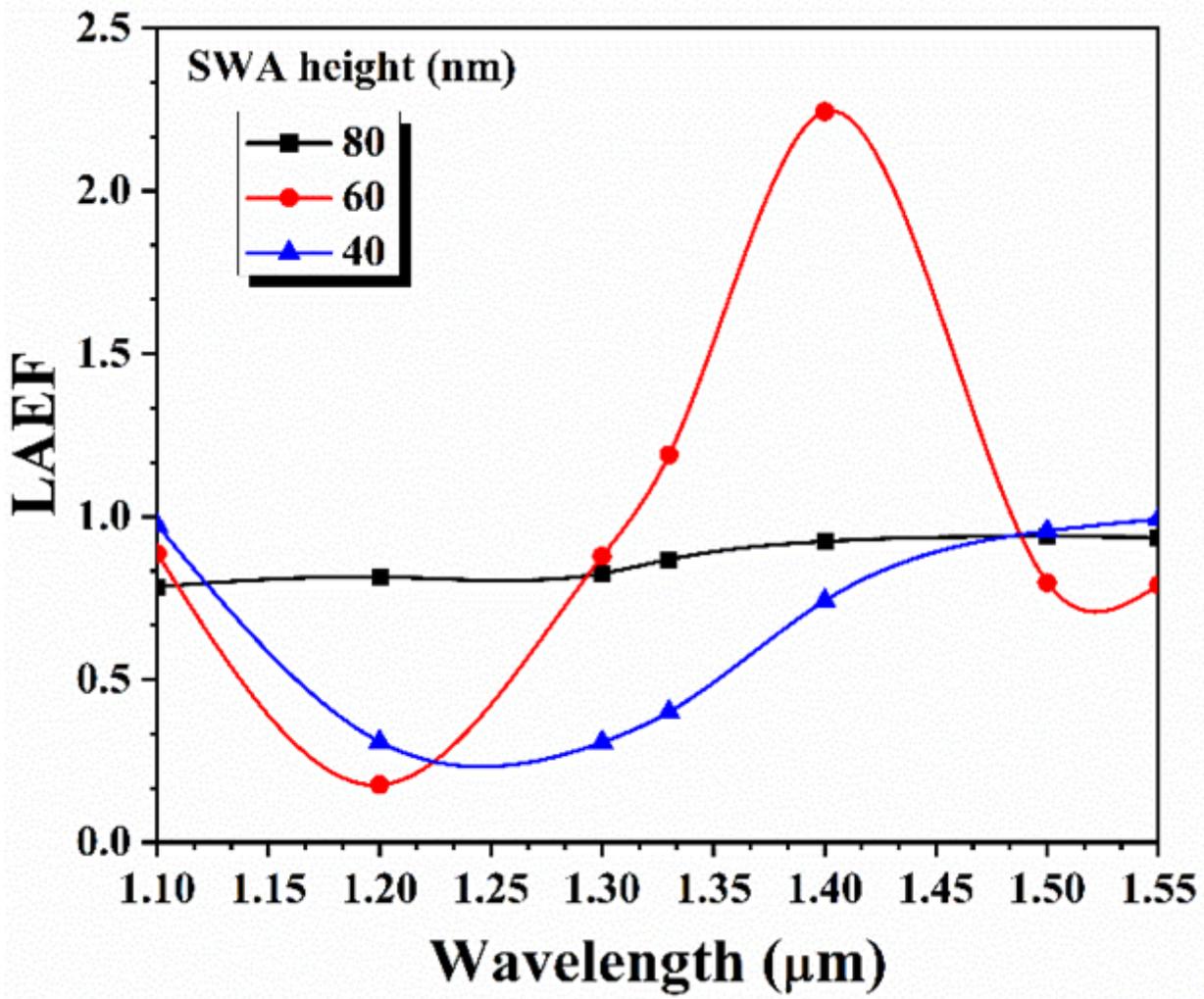


Figure 4

LAEF spectra vs Input wavelength at different values of SWA heights