Flat and Flexible 2D Plasmonic Crystal for Color Production

Neda Roostaei and Seyedeh Mehri Hamidi*

Magneto-plasmonics Lab, Laser and Plasma Research institute, Shahid Beheshti University, Tehran, Iran

***Corresponding author email:** m_hamidi@sbu.ac.ir

Regular paper: Received: Jan. 25, 2021, Revised: Sep. 8, 2021, Accepted: Oct. 22, 2021, Available Online: Oct. 24, 2021, DOI: 10.52547/ijop.15.1.93

ABSTRACT— Recently, color production by using plasmonic structures has widely been studied. In this research, a flat and flexible two-dimensional Kapton-copper plasmonic crystal with very low thickness has been fabricated in a new and optimal way. Color production is performed using our proposed plasmonic structure and different colors are achieved by changing the incidence angle of light. Also, the plasmonic resonance response of the fabricated structure has been recorded at the incidence angle of 58 degrees. Advantages of our proposed structure are low cost, easy fabrication, and very small dimensions, and thus this research can be useful due to the increasing needs for the integration and miniaturizing of optical devices in modern nanophotonic systems.

KEYWORDS: Colorimetry, Color Production, Plasmonic Crystal, Plasmonic Resonance.

I. INTRODUCTION

Colors play very important roles in human's daily life due to their abilities in carrying information. In general, there are three mechanisms for color production: a) partial absorption of light and reflection of the others, b) separating the different colors via the scattering, diffraction and material dispersion phenomena, and c) light emission at special wavelengths. The second method, in which colors originate from the interaction of light with micro/nanostructures, has been one of the most interesting scientific topics due to high resolution and contrast, and also high stability. Structural color was first studied by Load Rayleigh, who explained the blue color of sky with light scattering by nanoparticles [1]. Later, Gustov Mie developed the scattering model and successfully explained the colors of colloidal gold nanoparticles. Then the colors of metallic nanoparticles related to their structural information and thus the possibility of controlling the resonant properties has been provided [2]. Therefore, plasmonic nanostructures have widely been studied for color production due to their ability to manipulate the behavior of light through the surface plasmon resonance [3]-[10]. Plasmonic structural colors originate from the resonant coupling of light with free electrons (known as surface plasmon), and in these structures, resonant absorption of light (and reflection of the other part of the light) occurs, which can be used to produce color [11]-[14]. Plasmonic nanostructures have great potential for applications such as color filters [15], [16], wavelength selective photodetectors [17], optical cameras [18], [19], and so on. In addition, different colors can also be generated by plasmonic structure engineering, such as vertical nanorod arrays [20], cross nano antennas [21], isolated Au/Ag nano disks structures [22], metal–insulator–metal (MIM) nano resonators with an insulator sandwiched between two metallic materials [23], Aluminum dome-ring [24], and so on [25]-[27]. Plasmonic colors have a better resolution compared to pigment-based colors and are safe against the photo bleaching [16], [28].

The Kapton film has been selected as a flexible substrate in our proposed structure. The flexible

[Downloaded from ijop.ir on 2026-11-23]

Kapton tapes consist of polyimide (PM) film and silicone adhesive. Kapton film in addition to being flat and flexible, has advantages such as: high thermal conductivity [29], very low thickness and high mechanical and chemical stability. This flexible film has attracted many applications such as UV photodetectors [30], SERS chip [30], hydrogen sensing [32], high-electron mobility transistors (HEMTs) [33], and cardiovascular applications [34].

In this research, a flat and flexible 2D Kapton-copper plasmonic crystal with very low thickness has been fabricated and color production has been investigated using the proposed plasmonic crystal. Compared to the plasmonic nanostructures reported so far, the proposed plasmonic nanostructure has advantages such as low cost, simple fabrication process, miniaturization, flat and flexibility.

II. Experimental Methods

In this work, a flat and flexible 2D plasmonic crystal with very low thickness has been proposed and fabricated by the soft nanolithography method [35].

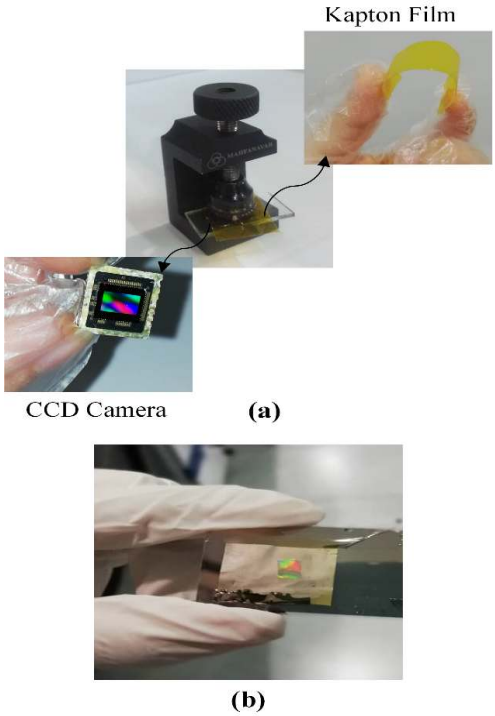


Fig. 1. (a) Sample preparation process, and (b) the fabricated plasmonic crystal.

A CCD camera was used to create two-dimensional pattern onto the Kapton tape. Sample preparation process is as follows: at first, a CCD extracted and separated from a camera, then a layer of the Kapton tape was placed onto the CCD by pressuring (Fig. 1(a)). After that, sample placed on the heater at 75^0C for 30 minutes. The sample was maintained under pressure at room temperature for one week to stabilize the two-dimensional pattern onto the Kapton tape. The Kapton tape has carefully been removed from the CCD after one week, and a 2D flexible structure with very low thickness has been achieved.

Finally, a thin layer of copper with a thickness of 35 nm is deposited on the 2D Kapton substrate. In this way, a flat and flexible 2D plasmonic crystal consisting of Kapton-copper has been achieved (Fig. 1(b)).

III. Results and Discussion

The SEM image of the fabricated plasmonic crystal is shown in Fig. 2 As can be seen, the fabricated plasmonic structure has a two-dimensional periodic pattern.

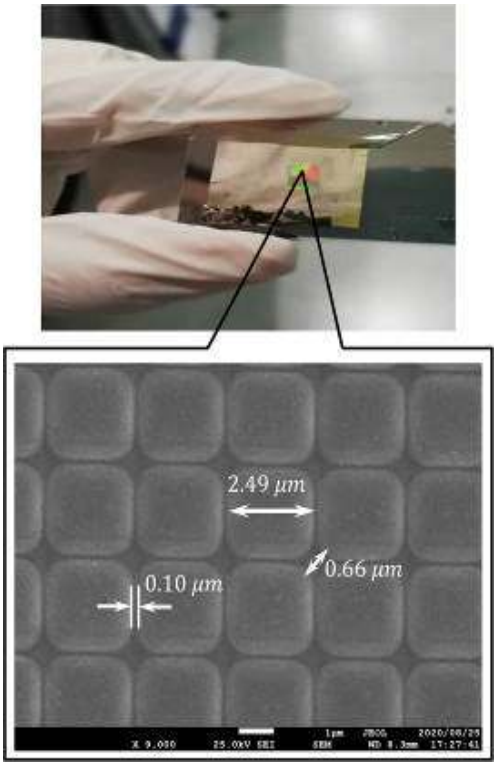


Fig. 2. SEM image of the fabricated plasmonic crystal.

[Downloaded from ijop.ir on 2026-11-23]

In addition, Energy-dispersive X-ray (EDX) analysis of the Kapton substrate was performed for the chemical characterization of the Kapton material. EDX analysis is an analytical method for characterization of the elemental and chemical composition of the sample. This technique is based on the interaction of X-ray excitation source and the specimens and shows the spectral peaks associated to the present element and their composition in the sample [36]. EDX analysis is a powerful tool for different biomedical fields or other works that require elemental characterization. The EDX result of the Kapton sample is shown in Fig. 3 According to the results, the Kapton substrate is mainly composed of silicon and it's a silicon-based material.

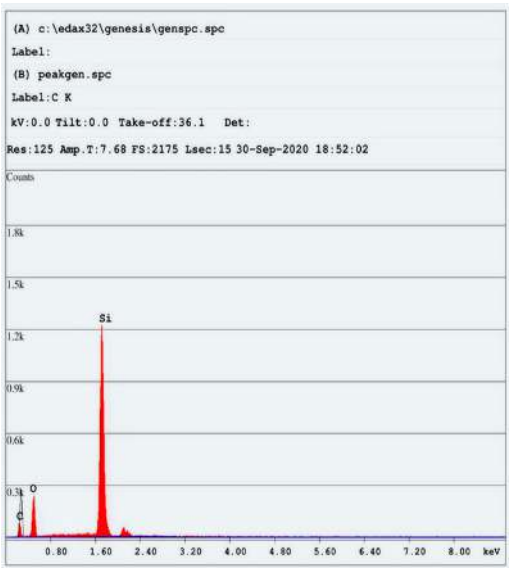


Fig. 3. EDX analysis of the Kapton substrate.

The absorption and transmittance spectra of the proposed plasmonic crystal were recorded using a UV-Visible spectrometer and are shown in Fig. 4 Also, the colorimetry diagram (CIE 1931) has been extracted using the absorption and transmittance data (Fig. 4(c)). As can be seen, the absorption and transmittance spectra of the fabricated plasmonic structure covers the green, yellow, and blue ranges of the visible region.

For a closer look, the reflection spectra of the sample measured at different incidence angles of 46, 52 and 58 degree (Fig. 5). Metallic nanoparticles arranged in a periodic array can exhibit extremely narrow and strong excitations which is known as plasmonic surface lattice resonance (SLR) [37], [38]. This phenomenon is result of the coupling between the diffracted order (DO) waves in a periodic structure and the localized surface plasmon resonances (LSPRs) coming from metallic nanowires in the sample related to individual NPs. The excitation of SLRs depends on different factors such as: the size and shape of the NPs, incidence angle of light, polarization, and optical surrounding environment (refractive index) [39]-[41].

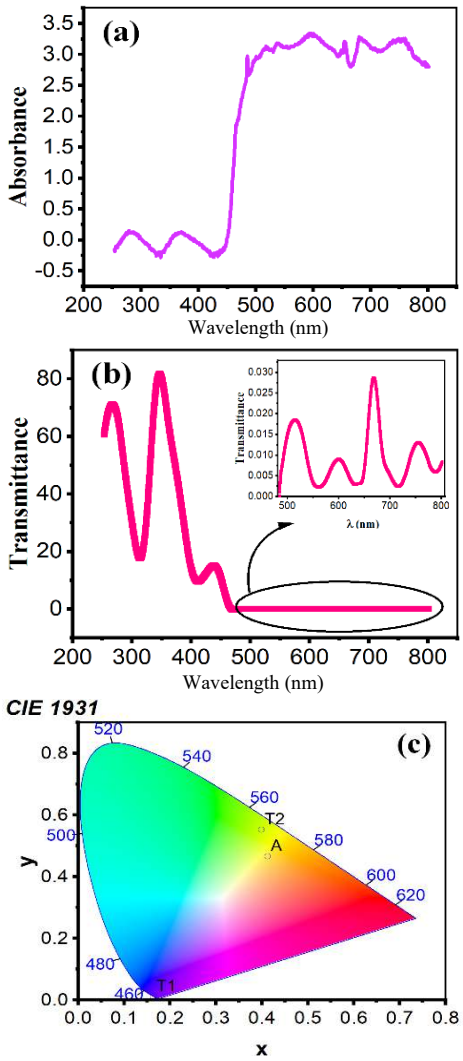


Fig. 4. (a) Absorption spectra, (b) transmittance spectra, and (c) extracted CIE colorimetry diagram of the sample.

The proposed plasmonic nanostructure composed of a two-dimensional array of Cu NPs and it can confirm the sharp diffracted order (DO) waves and LSPR modes. According

[Downloaded from ijop.ir on 2026-11-23]

to Fig. 5, surface lattice resonance (SLR) mode for the proposed plasmonic nanostructure has been observed in the reflection spectra. The weak SLR mode was achieved at the incidence angles of 46, and 52 degrees, while the sharper and stronger SLR mode was occurred at the incidence angle of 58^0 (Fig. 5).

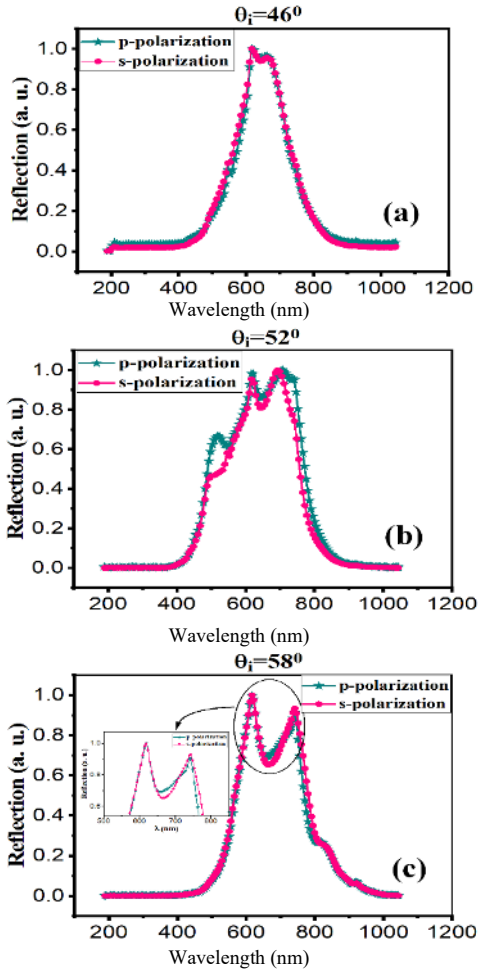


Fig. 5. Reflection spectra of the plasmonic structure under different incidence angles of (a) 46^0, (b) 52^0, and (c) 58^0 for s and p-polarization.

Also, the resonance dip wavelength is achieved at $\lambda_{res}\approx657$ nm for p-polarization, while it is occurred only with a red shift at $\lambda_{res}\approx665$ nm for s-polarization. This red shift can be explained according to the coupling of the dipole moment of each neighboring nanorods.

Finally, the colorimetry diagram (CIE diagram) has been extracted using the measured reflection spectra and is shown in Fig. 6 As can be seen, different colors have been created by changing the incidence angle. Therefore, the response of the fabricated plasmonic structure is angle-sensitive, which can be explained by considering the high angle-sensitivity of the plasmonic surface lattice resonance. This feature is an advantage for the proposed structure that can be used to produce adjustable colors.

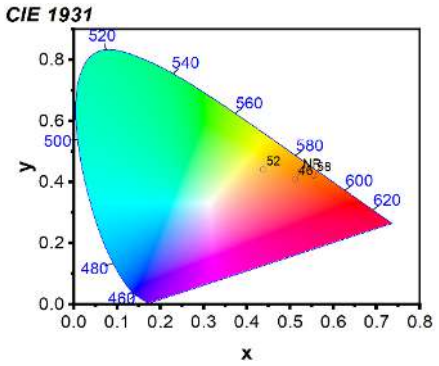


Fig. 6. CIE colorimetry diagram for different incidence angle of light.

IV. Conclusion

In this study, a flat and flexible 2D plasmonic crystal with very low thickness has been proposed and fabricated by the soft nanolithography method. Also, colorimetry diagram was extracted using the experimental data and color production is investigated using the proposed plasmonic structure. According to the results, different colors have been achieved by changing the incidence angle of light. In addition, the plasmonic resonance response of the fabricated structure has been measured at an angle of 58^0. Advantages of our proposed structure are low cost, simple fabrication, and very small dimension, and thus this research can be useful due to the increasing needs for the integration and miniaturizing of optical devices in modern nanophotonic systems.

References

[1] A.T. Young, "Rayleigh scattering," Appl. Opt. Vol. 20, pp. 533-535, 1981.

[2] K.L. Kelly, E. Coronado, L.L. Zhao, and G.C. Schatz, "The optical properties of metal nanoparticles: the influence of size, shape, and dielectric environment," Phys. Chem. B, Vol. 107, pp. 668-677, 2003.

[3] A. Kristensen, J.K. Yang, S.I. Bozhevolnyi, S. Link, P. Nordlander, N.J. Halas, and N.A.

[Downloaded from ijop.ir on 2026-11-23]

Mortensen, "Plasmonic colour generation," Nat. Rev. Mater. Vol. 2, pp. 1-14, 2016.

[4] W. Wang, D. Rosenmann, D.A. Czaplewski, X. Yang, and J. Gao, "Realizing structural color generation with aluminum plasmonic V-groove metasurfaces," Opt. Express, Vol. 25, pp. 20454-20465, 2017.

[5] M. Jalali, Y. Yu, K. Xu, R.J. Ng, Z. Dong, L. Wang, S.S. Dinachali, M. Hong, and J.K. Yang, "Stacking of colors in exfoliable plasmonic superlattices," Nanoscale Vol. 8, pp. 18228-18234, 2016.

[6] W. Wan, J. Gao, and X. Yang, "Full-color plasmonic metasurface holograms," ACS Nano Vol. 10, pp. 10671-10680, 2016.

[7] X. Zhu, C. Vannahme, E. Højlund-Nielsen, N. A. Mortensen, and A. Kristensen, "Plasmonic colour laser printing," Nat. Nanotech. Vol. 11, pp. 325-329, 2016.

[8] C. Yang, W. Shen, J. Zhou, X. Fang, D. Zhao, X. Zhang, C. Ji, B. Fang, Y. Zhang, X. Liu, and L.J. Guo, "Angle robust reflection/ transmission plasmonic filters using ultrathin metal patch array," Adv. Opt. Mater. Vol. 4, pp. 1981-1986, 2016.

[9] V.R. Shrestha, S.S. Lee, E.S. Kim, and D.Y. Choi, "Aluminum plasmonics based highly transmissive polarization-independent subtractive color filters exploiting a nanopatch array," Nano Lett. Vol. 14, pp. 6672-6678, 2014.

[10] Q. Chen and D.R. Cumming, "High transmission and low color cross-talk plasmonic color filters using triangular-lattice hole arrays in aluminum films," Opt. Express Vol. 18, pp. 14056-14062, 2010.

[11] W.L. Barnes, A. Dereux, and T.W. Ebbesen, "Surface plasmon subwavelength optics," Nature Vol. 424, pp. 824-830, 2003.

[12] A.V. Zayats, I.I. Smolyaninov, and A.A. Maradudin, "Nano-optics of surface plasmon polaritons," Phys. Rep. Vol. 408, pp. 131-314, 2005.

[13] E. Ozbay, "Plasmonics: merging photonics and electronics at nanoscale dimensions," Science Vol. 311, pp. 189-193, 2006.

[14] J.A. Schuller, E.S. Barnard, W. Cai, Y.C. Jun, J.S. White, and M.L. Brongersma, "Plasmonics for extreme light concentration and manipulation," Nat. Mater. Vol. 9, pp. 193-204, 2010.

[15] N. Ikeda, Y. Sugimoto, M. Ochiai, D. Tsuya, Y. Koide, D. Inoue, A. Miura, T. Nomura, H. Fujikawa, and K. Sato, "Color filter based on surface plasmon resonance utilizing sub-micron periodic hole array in aluminum thin film," IEICE Trans. On Electron. Vol. 95, pp. 251-254, 2012.

[16] R. Rajasekharan, E. Balaur, A. Minovich, S. Collins, T.D. James, A. Djalalian-Assl, K. Ganesan, S. Tomljenovic-Hanic, S. Kandasamy, E. Skafidas, D.N. Neshev, P. Mulvaney, A. Roberts, and S. Prawer, "Filling schemes at submicron scale: Development of submicron sized plasmonic colour filters," Sci. Rep. Vol. 4, pp. 6435-6444, 2014.

[17] B.Y. Zheng, Y. Wang, P. Nordlander, and N.J. Halas, "Color-selective and CMOS-compatible photodetection based on aluminum plasmonics," Adv. Mater. Vol. 26, pp. 6318-6323, 2014.

[18] S. Yokogawa, S.P. Burgos, and H.A. Atwater, "Plasmonic color filters for CMOS image sensor applications," Nano Lett. Vol. 12, pp. 4349-4354, 2012.

[19] Q. Chen, D. Das, D. Chitnis, K. Walls, T.D. Drysdale, S. Collins, and D.R.S. Cumming, "A CMOS image sensor integrated with plasmonic colour filters," Plasmonics Vol. 7, pp. 695-699, 2012.

[20] G. Si, Y. Zhao, J. Lv, M. Lu, F. Wang, H. Liu, N. Xiang, T.J. Huang, A.J. Danner, J. Teng, and Y.J. Liu, "Reflective plasmonic color filters based on lithographically patterned silver nanorod arrays," Nanoscale Vol. 5, pp. 6243-6248, 2013.

[21] T. Ellenbogen, K. Seo, and K.B. Crozier, "Chromatic plasmonic polarizers for active visible color filtering and polarimetry," Nano Lett. Vol. 12, pp. 1026-1031, 2012.

[22] K. Kumar, H. Duan, R.S. Hegde, S.C. Koh, J.N. Wei, and J.K. Yang, "Printing colour at the optical diffraction limit," Nat. Nanotech. Vol. 7, pp. 557-561, 2012.

[23] W. Yue, S. Gao, S.S. Lee, E.S. Kim, and D.Y. Choi, "Highly reflective subtractive color filters capitalizing on a silicon metasurface integrated with nanostructured aluminum mirrors," Laser & Photonics Rev. Vol. 11, pp. 1600285-1600292, 2017.

[Downloaded from ijop.ir on 2026-11-23]

[24] A.E. Miroshnichenko, S. Flach, and Y.S. Kivshar, "Fano resonances in nanoscale structures," Rev. Mod. Phys. Vol. 82, pp. 2257-2298, 2010.

[25] X. Duan, S. Kamin, and N. Liu, "Dynamic plasmonic colour display," Nat. Commun. Vol. 8, pp. 1-9, 2017.

[26] D. Franklin, Y. Chen, A. Vazquez-Guardado, S. Modak, J. Boroumand, D. Xu, S.T. Wu, and D. Chanda, "Polarization-independent actively tunable colour generation on imprinted plasmonic surfaces," Nat. Commun. Vol. 6, pp. 1-8, 2015.

[27] M.L. Tseng, J. Yang, M. Semmlinger, C. Zhang, P. Nordlander, and N.J. Halas, "Two-dimensional active tuning of an aluminum plasmonic array for full-spectrum response," Nano Lett. Vol. 17, pp. 6034-6039, 2017.

[28] K. Kumar, H. Duan, R.S. Hegde, S.C. Koh, J.N. Wei, and J.K. Yang, "Printing colour at the optical diffraction limit," Nature nanotechnol. Vol. 7, pp. 557-561, 2012.

[29] D.J. Benford, T.J. Powers, and S.H. Moseley, "Thermal conductivity of Kapton tape," Cryogenics Vol. 39, pp. 93-95, 1999.

[30] A.F. Abdulrahman, S.M. Ahmed, N.M. Ahmed, and M.A. Almessiere, "Fabrication, characterization of ZnO nanorods on the flexible substrate (Kapton tape) via chemical bath deposition for UV photodetector applications," AIP Conference Proceedings Vol. 1875, pp. 020004-020008, 2017.

[31] X. Zhou, H. Li, G. Yu, Y. Chen, Y. Wang, Z. Zeng, and L. Chi, "A Highly-efficient, Stable and Flexible Kapton Tape-based SERS Chip," Mater. Chem. Front. Vol. 5, pp. 6471-6475, 2021.

[32] J.J. Hassan, M.A. Mahdi, S.J. Kasim, N.M. Ahmed, H.A. Hassan, and Z. Hassan, "Fast UV detection and hydrogen sensing by ZnO nanorod arrays grown on a flexible Kapton tape," Mater. Sci.-Polandm Vol. 31, pp. 180-185, 2013.

[33] K.L. Hsu and M.C. Wu, "Fabrication and Characterization of Flexible AlGaN/GaN HEMTs on Kapton Tape," IEEE Trans. Electron Devices Vol. 68, pp. 3320-3324, 2021.

[34] E. Lindner, V.V. Cosofret, S. Ufer, R.P. Buck, R.P. Kusy, R.B. Ash, and H.T. Nagle, "Flexible (Kapton-based) microsensor arrays of high stability for cardiovascular applications," J. Chem. Soc. Faraday Trans. Vol. 89, pp. 361-367, 1993.

[35] M. Ghasemi, N. Roostaei, F. Sohrabi, S.M. Hamidi, and P.K. Choudhury, "Biosensing applications of all-dielectric SiO 2-PDMS meta-stadium grating nanocombs," Opt. Mater. Express, Vol. 10, pp. 1018-1033, 2020.

[36] R.K. Mishra, A.K. Zachariah, and S. Thomas, "Energy-dispersive X-ray spectroscopy techniques for nanomaterial," Microscopy Methods Nanomaterials Characterization, pp. 383-405, 2017.

[37] A.I. Väkeväinen, R.J. Moerland, H.T. Rekola, A.P. Eskelinen, J.P. Martikainen, D.H. Kim, and P. Törmä, "Plasmonic surface lattice resonances at the strong coupling regime," Nano Lett. Vol. 14, pp. 1721-1727, 2014.

[38] V.G. Kravets, A.V. Kabashin, W.L. Barnes, and A.N. Grigorenko, "Plasmonic surface lattice resonances: a review of properties and applications," Chem. Rev. Vol. 118, pp. 5912-5951, 2018.

[39] J.J. Mock, M. Barbic, D.R. Smith, D.A. Schultz, and S. Schultz, "Shape effects in plasmon resonance of individual colloidal silver nanoparticles," J. Chem. Phys. Vol. 116, pp. 6755-6759, 2002.

[40] W.A. Murray and W.L. Barnes, "Plasmonic materials," Adv. Mater. Vol. 19, pp. 3771-3782, 2007.

[41] W.A. Murray, J.R. Suckling, and W.L. Barnes, "Overlayers on silver nanotriangles: field confinement and spectral position of localized surface plasmon resonances," Nano Lett. Vol. 6, pp. 1772-1777, 2006.



Neda Roostaei received her B.S. degree in Optics and Laser from Shahid Bahonar University, Kerman, Iran in 2014, M.Sc. degree in Photonics from Alzahra University, Tehran, Iran in 2016. She is currently a Ph.D. student in the Magneto-Plasmonic Lab, Laser and Plasma

[Downloaded from ijop.ir on 2026-11-23]

Research Institute, Shahid Beheshti University, Tehran, Iran. Her research interests include Metasurfaces, Plasmonic Imaging, TIRF Microscopy, Plasmonic and nanophotonic.



Seyedeh Mehri Hamidi received her Ph.D. degree in photonics from Laser and Plasma Research Institute, Shahid Beheshti University, Iran, in 2009. She is currently the director of Magneto-Plasmonic Lab of Laser and Plasma Research Institute. She works on the research fields of magneto-plasmonic, nanophotonic, neurophotonics, piezotonics, photonic and magnetophotonic crystals, Surface Plasmon Resonance, dielectric and magnetic nanostructures.

[Downloaded from ijop.ir on 2026-11-23]

THIS PAGE IS INTENTIONALLY LEFT BLANK.

[Downloaded from ijop.ir on 2026-11-23]