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Research paper

A study of nano-structural effect on the polarization characteristics of metallic sub-wavelength grating polarizers in visible wavelengths

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ABSTRACT

The structural effect of subwavelength gratings as the polarizer on the polarization characteristics in visible wavelengths (400–700 nm) is systematically investigated through both numerical simulation with Finite Difference Time Doman algorithm and experiments. The grating parameters such as the material, the pitch, the duty cycle, the height and the cross-sectional shape of the grating are addressed in this work. The optimized range for those parameters is worked out, based on the desired performance margin at the level of 70% transmittance and 50:1 for the extinction ratio. Polarization performance such as the transmittance over 70% and the extinction ratio above 50:1 has been experimentally demonstrated by the 200 nm pitched grating in Al with the height of 150 nm, which was fabricated by high resolution electron beam lithography in this work, guided by the simulation result. Au grating as the polarizer was also compared but ruled out in this work because of the poor performance in polarization. This work is essential in developing grating based polarizers for polarimetric detection and imaging in visible wavelengths.

1. Introduction

Polarimetric detection, capable of sensing weak signals by enhancing imaging contrast at all orientations of polarized lights, is widely applied in underwater detection, target recognition and camouflage removal [1–3]. The latest technology for pixelated polarimetric imaging is to utilize metallic sub-wavelength gratings as polarizers with four different polarization directions [4–7]. Although such kind of pixelated polarizers as discrete components have already been commercialized with high performance as far as the transmittance and extinction ratio concerned, the monolithic integration of the gratings to detectors for a miniaturized polarimetric detection system still remains a big challenge because of the unsatisfactory transmittance as well as the low extinction ratio. For example, Wang et al. successfully integrated the Au gratings into the InP/InGaAs polarization detector at 1.0–1.6 μm band, the extinction ratio is merely 18:1 [8], far from high quality imaging. It is understood that the parabolic cross-sectional shape should be responsible for such a low ratio. Al gratings with square shaped cross-section, formed by dry etch in chlorine-based plasma, had been reported with the extinction ratio of 75:1 [9]. Such an improvement of the extinction ratio suggests that the polarization performance is closely governed by the nanoscale structures. It is naturally believed that the structural effect should become stronger in visible wavelengths (400–800 nm) than in infrared ones because the grating pitch becomes shorter. So far, to the best of our knowledge, there has been extremely limited reports addressing the effect of the grating structure on the transmittance/extinction ratio.

This work conducts a systematic study of the structural effect on the polarization performance in the visible band in hopes to achieve the transmittance of the transverse magnetic wave (TM) ≥70% and the extinction ratio (TM/TE) beyond 50:1 for practical applications. The parameters affecting the grating performance, such as the materials, the duty cycle, the thickness and the cross-section shape of the gratings, are systematically investigated. Both the transmittance and the extinction ratio are calculated by Finite Difference Time Domain (FDTD) simulations to figure out the optimized window. The grating shapes as

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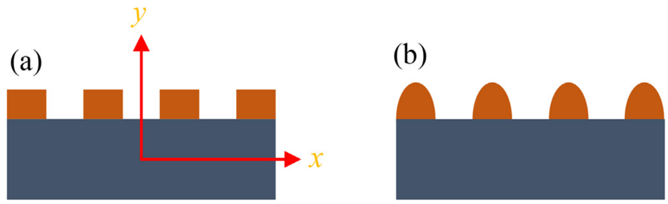

Fig. 1. Schematic diagrams for the cross-section view of the metallic gratings used in the simulation. Two different cross-sectional shapes as rectangle (a) and parabola (b), as well as two different materials as Al and Au of the gratings on the SiO_2 substrate, are used as the simulation parameters.

Table 1
Simulating parameters.

Grating shape	rectangle, parabola
Wavelength	400–800 nm
Material	Al, Au
Substrate	SiO_2
Thickness (t)	100–150 nm
Period (p)	200, 400 nm
Duty cycle (d)	0.4, 0.5, 0.6

parabolic, square and the combination of these two are also compared. Using the simulation results as a guide, sub-wavelength gratings in Al with the thickness of 150 nm were successfully fabricated on quartz substrates by electron beam lithography, followed by a thermal evaporation of an Al film and ended with a lift-off process. Optical characterization proves that the fabricated Al gratings as polarizers with optimized parameters meet the desired performance.

2. Simulation study of the structural effect

Fig. 1 shows two different cross-sectional shapes of the gratings: rectangle and parabola on a SiO_2 substrate. Two different materials of Au and Al, respectively, are compared.

Table 1 summarizes the parameters to be studied. In the FDTD simulation, Palik model [10] is applied for the metals of both Au and Al. The periodical boundary condition is adapted in x-direction and the Perfect Matching Layer condition is in y-direction [10]. The FDTD mesh accuracy is 4.

For the ideal grating structure with the rectangular profile as illustrated in Fig. 1a, the materials of Al and Au for the gratings with the pitch of 200 and 400 nm, respectively, and the duty cycle fixed as 0.5, are compared, as presented in Fig. 2(a-b). The red color dashed-lines in the plots of Fig. 2(c-d) define the normalized transmittance at 70% and the extinction ratio at 50:1 as the margin, respectively, for practical applications. It can be seen that both the TM transmittance and the extinction ratio of TM/TE through 200 nm pitched Al gratings has much better performance in the whole band than that through Au ones, when the thickness is 100 nm. Therefore, Al is utilized in the work for the grating based polarizer. In the case of 400 nm period, Al gratings and Au gratings with the thickness of 100 nm excite the surface plasmon at the wavelength of 580 nm and 610 nm respectively, resulting in the decrease of both the TM transmittance and extinction ratio.

In practice, however, the fabricated Al gratings often have a parabolic-like profile [11], as schematically illustrated in Fig. 1b, such that the extinction ratio is considerably reduced [11]. Taking the parabolic

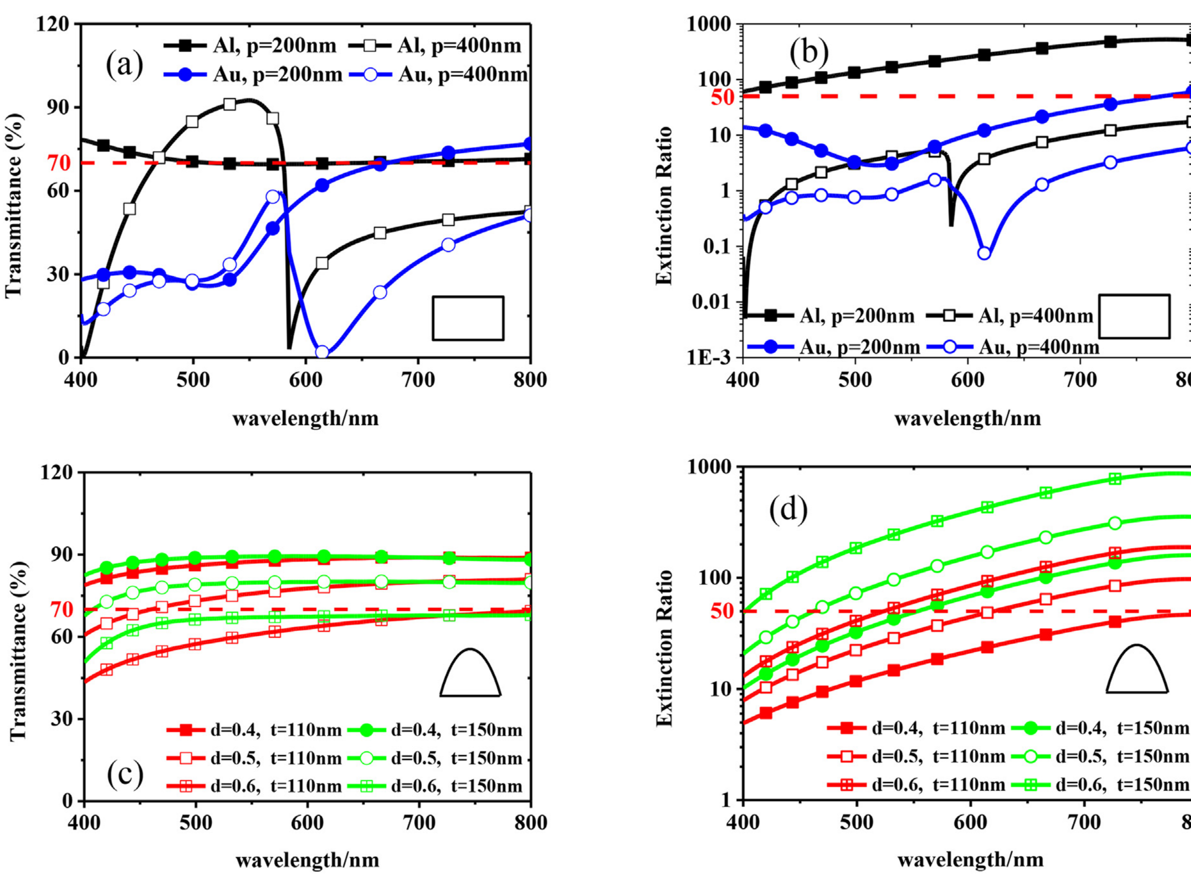

Fig. 2. The results of numerical simulations by the FDTD method for the subwavelength gratings on quartz. (a) The TM transmittance and (b) the extinction ratio of Al and Au metal gratings with rectangular cross section. The grating pitch is 200 nm and 400 nm, respectively, with the duty cycle fixed as 0.5. (c) The TM transmittance and (d) the extinction ratio of parabolic Al gratings with the thicknesses of 110 nm and 150 nm, respectively. Different duty cycles from 0.4 to 0.6 are also compared.

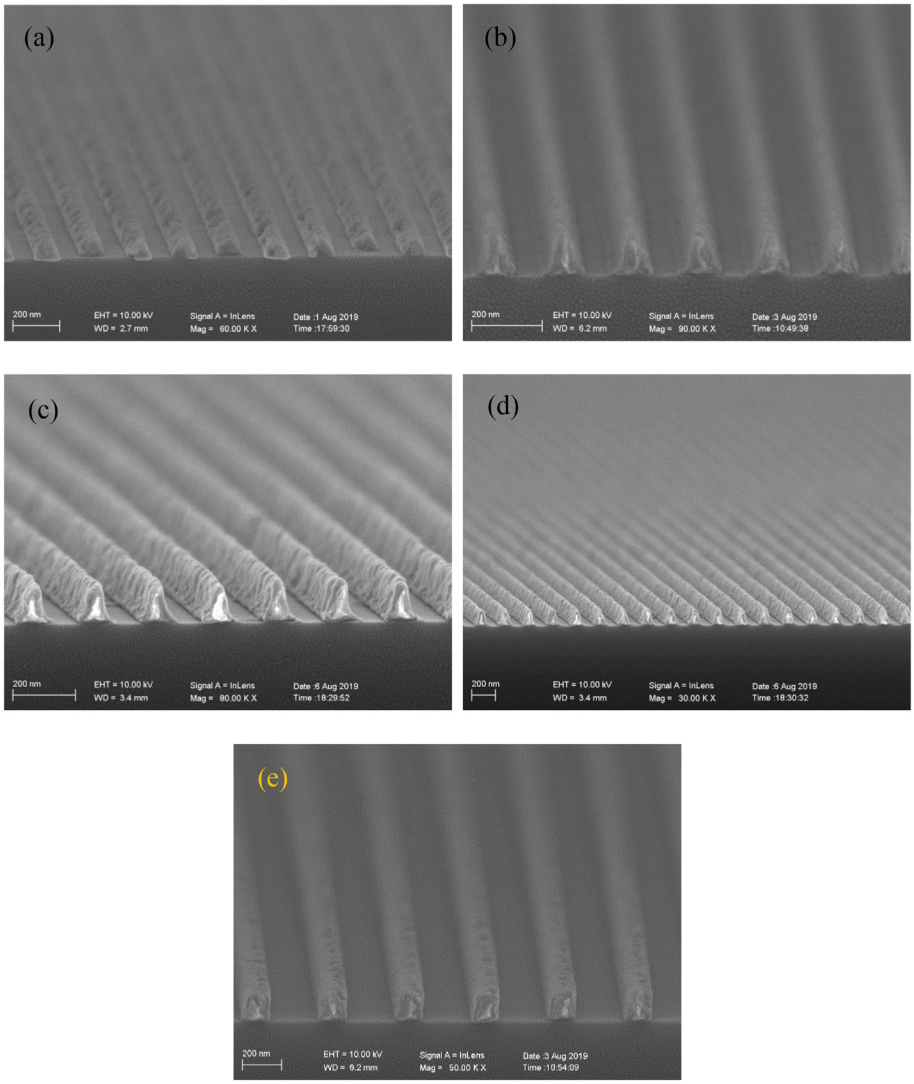

Fig. 3. The fabricated Al gratings with the thickness of 50 nm (a), 100 nm (b) and 150 nm (c-d), and Au gratings with the thickness of150 nm (e) on the quartz wafer.

profile into consideration, the influence of the duty cycle (0.4, 0.5 and 0.6) and the thickness (110 nm and 150 nm) of the gratings on the polarization performance is comprehensively investigated. It can be seen from Fig. 2(c-d) that the TM transmittance and the extinction ratio can be enhanced by increasing the thickness of the gratings with the same duty cycle. For the same thickness, increasing the duty cycle will reduce the transmittance of TM wave, but enhance the extinction ratio. Therefore, optimization of the parameters is necessary for maximizing both the transmittance and the extinction ratio.

From Fig. 2c, the transmittance of the TM wave beyond the 70% margin corresponds to the duty cycle of 0.4 (the grating thickness over 110 nm) or 0.5 (the thickness over 150 nm), completely ruling out the duty cycle of 0.6 as the transmittance is below the margin of 70%. From Fig. 2d, only the duty cycle of 0.5 with the thickness over 150 nm of the grating satisfies the criteria at 50:1. Combining the simulation results for both the transmittance and the extinction ratio, the optimized parameters of the Al grating should be 0.5 for the duty cycle and 150 nm for the grating thickness with the pitch of 200 nm. The simulation results for the grating parameters are then adapted in the nanofabrication of polarizers in this work.

3. Nanofabrication of the subwavelength gratings in Al and Au

Nanofabrication of the Al and Au gratings for polarizers in the visible band on quartz wafers was carried out by the state-of-the-art electron beam lithography, followed by the metallization of Al and Au and lift-off process, using the optimized parameters as discussed above. A bi-layer of 200 nm PMMA-MAA (EL 6)/150 nm PMMA(MW350K) was first coated and then baked in oven for 1 h at 180 °C. To avoid charging effect during the e-beam exposure, a 60 nm conducting e-spacer layer, supplied by All-resist Ltd., was spin-coated on the top of the resists, and baked on a hot plate at 90 °C for 2 min. E-beam exposure was carried out by a professional beamwriter, JEOL JBX6300 with a beam of 10 nm as the beam-spot size at 100 keV as the acceleration tension. The exposure dose is about 383–437 μC/cm^2. After exposure, the e-spacer was first removed by rinsing in deionized water for 2 min before the routine developing process in the mixture of MIBK and IPA (1:3) for 60 s at 23 °C. The developed resist was finally rinsed in IPA for 30 s. The Al film with three different thicknesses of 50 nm, 100 nm and 150 nm and the Au film with the thickness of 150 nm were deposited by thermal evaporation in high vacuum, supplied by Kurt J. Lesker Ltd. (Nano 36). The unwanted Al and Au was finally removed by lift-off in acetone. Fig. 3(a-d) presents the micrographs by a scanning electron microscope (SEM), Zeiss Sigma HD, showing the fabricated gratings in Al on quartz wafer. The cross-sectional views of the Al gratings show the clear parabolic shape of the lines. In the meantime, 150 nm thick Au gratings with the pitch of 300 nm were presented by the SEM photos in Fig.3e. In contrast to the Al gratings, rectangle-like cross-section shape

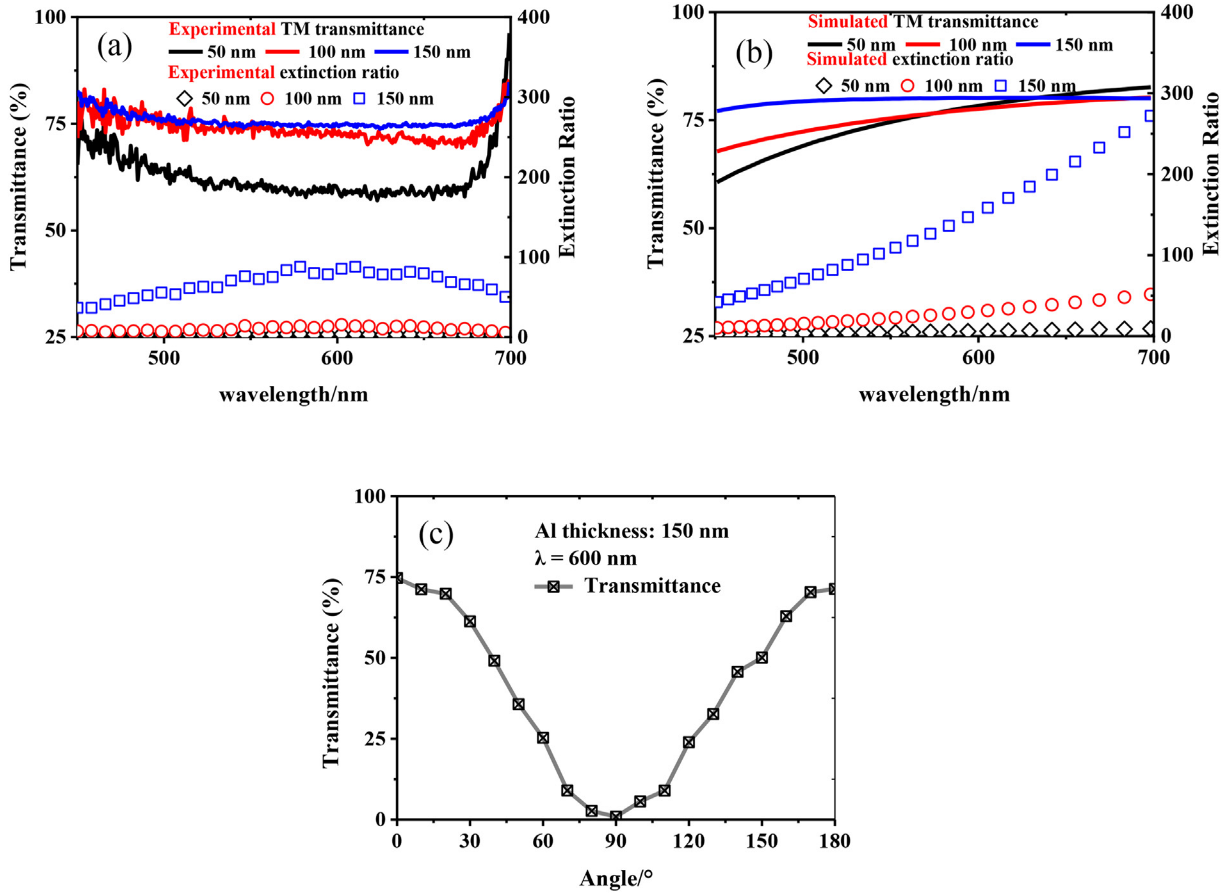

Fig. 4. The experimental (a) and simulated (b) polarization properties of Al gratings with thickness of 50 nm, 100 nm and 150 nm. (c) The experimental polarization behavior of the transmitted light for the linear incident light at 600 nm for the thickness of 150 nm.

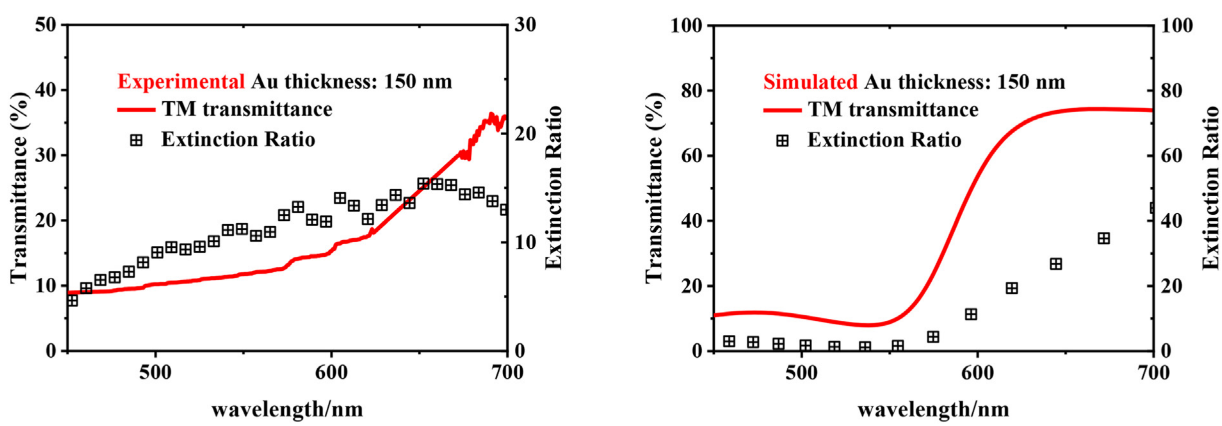

Fig. 5. The experimental (a) and simulated (b) polarization properties of Au gratings with the thickness of 150 nm.

is observed in the Au gratings. The origin of such a difference in the cross-sectional shape is explained by Xu et al., [11]. This work focuses on how the cross-sectional shape governs the polarization property to the transmitted light.

4. Optical characterizations

Optical characterization was carried out to demonstrate the polarization performance of the fabricated Al gratings on SiO_2 by a standard Nova Visible spectrum testing equipment in the wavelengths of 450-700 nm. The measurement area in optical characterization is 200 μm × 200 μm. Fig.4 presents the measured transmittance and the extinction ratio from the gratings with the thickness of 50 nm, 100 nm and 150 nm, respectively.

Although the experimental TM transmittance of the 100 nm thick Al-grating (Fig. 4a) is over 70%, its extinction ratio is only about 10:1, which is far below the margin. For the gratings with the thickness of 150 nm as shown in Fig. 4a, the TM transmittance is beyond 75%, and the extinction ratio in the major visible band from 490 nm to 700 nm is well over the criteria of 50:1. The maximum peak reaches 90:1. Therefore, increasing the grating thickness is certainly an effective method for enhancing the extinction ratio. Compared with Fig. 4b, the polarization characteristics of the experiments are in accordance with the theory, but the maximum extinction ratio is different under the thickness of 150 nm. The reason may lie in the defects of the fabricated Al gratings, while it can still be seen that the theoretical value is still in line with the situation of low thickness.

Fig. 4c shows the transmittance vs the polarization angle at the wavelength of 600 nm from the fabricated Al grating with the thickness of 150 nm. Clear polarization behavior is observed.

To compare the polarization of Au grating with that of Al one, the fabricated Au grating with the thickness of 150 nm on a quartz wafer was also optically characterized. Fig. 5a illustrates the transmittance and the extinction ratio of the fabricated Au gratings with the thickness of 150 nm. In the wavelengths from 500 nm to 600 nm, the light transmittance is extremely low because of the absorption by Au in this band. Unfortunately, even in the wavelengths from 600 nm to 700 nm, the measured transmittance is still well under the margin. Moreover, the maximum extinction ratio of the Au grating is about 20:1. Compared with Fig. 5b, it can be seen that the measured transmittance of the 300 nm pitched Au grating agrees with the theoretical calculation qualitatively. The low transmittance measured in the fabricated grating may be caused by the defects and deviations in the shape from the model. Nevertheless, it can be concluded that Au is not a suitable material for polarizers based on subwavelength gratings, and it should be excluded for the further development of miniaturized polarimetric detection system.

5. Conclusion

By studying how the nanostructure governs the polarimetric property of a grating based polarizer, both theoretically and experimentally, this work successfully figured out the optimized parameters of the grating for achieving high performance of polarization. It was found that Al material, instead of Au, is suitable for the subwavelength gratings on quartz. Using the calculated parameters such as the pitch of 200 nm, the height of 150 nm, the duty cycle of 0.5, the fabricated Al grating on quartz demonstrated outstand polarimetric performance as 70% transmittance with 50:1 extinction ratio. It was also found that although the parabolic shape of the fabricated Al grating could reduce the extinction ratio, the increase in height can surely enhance the extinction ratio without losing the transmittance. The result and the conclusion made in this work is extremely important for the further development of grating based polarizers.

Declaration of Competing Interest

The authors do not have any possible conflict of interest.

Acknowledgments

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References

[1] K. Shiraishi, S. Oyama, C.S. Tsai, A polarizer using thin metallic-film subwavelength grating for infrared to terahertz region, J. Lightwave Technol. 29 (2011) 670–676.
[2] A.G. Andreou, Z.K. Kalayjian, Polarization imaging: principles and integrated polarimeters, IEEE Sensors J. 2 (2003) 566–576.
[3] J.S. Tyo, D.L. Goldstein, D.B. Chenault, J.A. Shaw, Review of passive imaging polarimetry for remote sensing applications, Appl. Opt. 45 (2006) 5453–5469.
[4] V. Gruev, R. Perkins, T. York, CCD polarization imaging sensor with aluminum nanowire optical filters, Opt. Express 18 (2010) 19087–19094.
[5] S. Gao, R. Njuguna, V. Gruev, Fabrication and performance evaluation of pixelated nano-wire grid polarizer, Proc. SPIE 8873 (2013) 88730L.
[6] V. Gruev, A. Ortu, N. Lazarus, J.V. Spiegel, N. Engheta, Fabrication of a dual-tier thin film micropolarization array, Opt. Express 15 (2007) 4994–5007.
[7] J. Guo, D. Brady, Fabrication of thin-film micropolarizer arrays for visible imaging polarimetry, Appl. Opt. 39 (2000) 1486–1492.
[8] R. Wang, T. Li, X.M. Shao, X. Li, X.Q. Huang, J.H. Shao, Y.F. Chen, H.M. Gong, Subwavelength gold grating as polarizers integrated with InP-based InGaAs sensors, ACS Appl. Mater. Interfaces 7 (2015) 14471–14476.
[9] Z.G. Zhang, F.L. Dong, T. Cheng, K. Qiu, Q.C. Zhang, W.G. Chu, X.P. Wu, Nanofabricated pixelated micropolarizer array for visible imaging polarimetry, Rev. Sci. Instrum. 85 (2014) 105002.
[10] A. Taflove, S.C. Hagness, Computational Electrodynamics: The Finite-Difference Time-Domain Method, 3rd edition, Artech House, 2005.
[11] C. Xu, J.N. Deng, X.Q. Huang, T. Li, X. Li, X.M. Shao, R. Wang, H.M. Gong, S.C. Zhang, J.H. Shao, Y.F. Chen, Integrating subwavelength polarizers onto InP-InxGa1 − xAs sensors for polarimetric detection at short infrared wavelength, Photonics Nanostruct. Fundam. Appl. 33 (2019) 10–15.