Journal of Alloys and Compounds 621 (2015) 244–249

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jalcom

Duty cycle dependency of the optical transmission spectrum in an ultrathin nanostructured Ag film

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ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form 9 September 2014
Accepted 26 September 2014
Available online 5 October 2014

Keywords:
Plasmonic
Color filter
Duty cycle
LSPP
SRSPP

ABSTRACT

Plasmonic color filters with a single periodically patterned metal film structure deposited on a glass substrate have been an attractive research hotspot due to its ease of fabrication, durability and flexible color tunability. Previous researches mostly focused on the periodicity, shape, thickness dependency of the transmission spectrum. Here, we both theoretically and experimentally studied the influence of duty cycle to the transmission spectrum of ultrathin Ag film patterned with one dimensional grating. It is found that the transmission minimum could be largely tuned by varying the duty cycle. The physical mechanism for the degradation of the transmission spectrum when increasing duty cycle and period of Ag grating has been discussed.

1. Introduction

Plasmonic color filters based on periodically nanostructured metal films have been widely studied recent years [1–11]. They represent an attractive approach for on chip color filters, which are vital components for future displays, image sensors, digital photography, projectors and other optical measurement instrumentation due to their stability, ease of fabrication, high space resolution, and high color tunability. While traditional colorant filters are vulnerable to processing chemicals, and suffer from performance degradation under long-duration ultraviolet irradiation or at high temperatures. Additive color filters (ACFs) based on the well-known extraordinary optical transmission (EOT) phenomenon [12–14] could accomplish color filtering by reject the entire visible spectrum except for the selective transmission band that is associated with the excitation of Surface Plasmon Polaritons (SPPs) on the surface of a single optical thick nanostructured metal film. The transmission band could be easily tuned through the entire visible spectrum by changing the geometric parameters, leading to high color tunability. However, the transmission peak of this color filter is relatively low (40–50%) [5] for the rejection of the major part of the visible spectrum. A plasmonic subtractive color filter (SCF) based on extraordinary low transmission (ELT) was proposed by Zeng et al. [8] to improve the transmission (up to 60–70%). They used an ultrathin nanostructured metals to reject one particular wavelength band and transmit the remaining major part of the visible spectrum, thus improved the total transmission and achieved the color filtering of the complementary color corresponding to the transmission minimum wavelength. Seemingly, the transmission minimum can be spectrally tuned by simply adjusting the geometric parameters, namely periodicity, shape and size of the nanostructure.

To our knowledge, most previous studies to tune the spectrum of the color filter are focused on the material selection [15–17], periodicity [8,18], array shape [5], and thickness [18] of the nanostructure. West et al. [15] studied pure metals, alloys, heavily doped wideband semiconductors and graphene to find the best low-loss plasmonic material for particular frequency and application. They found that silver is the better material in local surface plasmon polaritons (LSPPs) and SPP applications in visible and near infrared ranges in terms of its quality factor. The authors also noted that there is not one single clear choice for the best low-loss plasmonic material for all applications and many other aspects, such as fabrication practicality and cost, should be considered to make the final choice. Yang et al. [16] considered aluminum silver alloy as plasmonic material, and provided a method to change the interband transition energy. This alloy significantly decreases the dissipative loss by varying the annealing temperature. They further compared aluminum silver

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http://dx.doi.org/10.1016/j.jallcom.2014.09.202
0925-8388/

alloy with typical plasmonic material Cu and Au and came to a conclusion that the alloy is a better choice only within wavelengths below 650 nm. An aluminum platinum alloy for a plasmonic material in a particular frequency was also reported [17]. Yokogawa et al. [5] reported on the optical performance of a hexagonally packed subwavelength sized hole array on Al film, and found that the transmission properties of the hexagonal hole array filters are extremely robust with respect to array size, random defects, and spatial crosstalk from neighboring filters of different color compared with square hole array. In our previous work [18], effects of film thickness and grating period on color filter with one-dimensional Ag grating film were systematically studied. It is found that the wavelength of transmission minimum undergoes a redshift with increasing grating period and decreasing film thickness. However, so far no systematical investigation has been reported on the effect of duty cycle (the ratio of Ag width to the period) on the periodic nanostructure to color filter. In this work, we carried out a systematical study on the effect of duty cycle on the spectral performance in one-dimensional Ag grating nanostructure deposited on a glass substrate with different film thicknesses and periods. We reveal that the duty cycle can indeed largely influence the color filter behavior. Possible mechanisms for obtained results are discussed.

2. Simulation and experimental details

2.1. Simulation details

To systematically investigate the influence of duty cycle to the performance of plasmonic color filter, we simulated a series of periods and film thicknesses of nanostructured Ag films as depicted in Table 1.

Fig. 1 shows the schematic illustration of the structure studied here. w is the width of the Ag line, s is the width of the slit, d is the thickness of the Ag film, p is the period and the duty cycle $c = w/p$.

All of the simulations were carried out by three dimensional FDTD methods using the Lumerical commercial software package (Lumerical Solutions Inc.). The complex dielectric constants, n and k, of the ultrathin Ag film used in simulations are from Palik (0–2 μm) [19], in which a series of n and k data experimentally determined at different wavelengths for Ag films were fitted with a tolerance of 0.1 and max coefficients of 6. A unit cell consisting of one Ag strip was used with periodic boundary conditions to simulate an infinite array of periodic nanogratings. Perfectly matched layer boundary conditions (PML) were used in the vertical direction to prevent non-physical scattering at the edge of the simulation box. A TM (transverse magnetic) polarized white light containing wavelengths from 380 nm to 780 nm incidents normally from the substrate to the Ag film.

Table 1
Simulation parameters for the influence of duty cycle on the performance of plasmonic color filter of nanostructured Ag films.

	Start	End	Increment
Period (nm)	100	450	50
Film thickness (nm)	15	45	10
Duty cycle	0.1	0.9	0.01
Wavelength (nm)	380	780	2

2.2. Preparation method and characterization

For the preparation of one-dimensional Ag metallic film nanograting, Ag films on glass substrate (roughness of about 1 nm) were magnetron sputtered using a direct-current magnetron sputtering system (DCMS, JZCK-400) in a vacuum of 2×10^{-4} Pa chamber under purified argon atmosphere. The thickness of deposited films was characterized by synchrotron radiation X-ray reflectivity (SR-XRR) at beamline BL14B1 of the Shanghai Synchrotron Radiation Facility (SSRF) at a wavelength of 0.124 nm. Nanograting structure of as-deposited Ag film was fabricated by using focused ion beam machine (FIB) and its microstructure was monitored by field-emission scanning electron microscopy (FE-SEM, Hitachi S-4800). Optical microscope images of the nanograting under TM-polarized white light illumination were measured using a microscope (Nikon 80i).

3. Results

In the present work, we studied the effect of duty cycle on spectral performance of a one-dimensional Ag nanograting film deposited on a glass substrate. Firstly, gratings with fixed period $p = 100$ nm and film thickness $d = 15$ nm, but various duty cycles $c = 0.4$, 0.55 and 0.7 were simulated, respectively. Fig. 2 shows

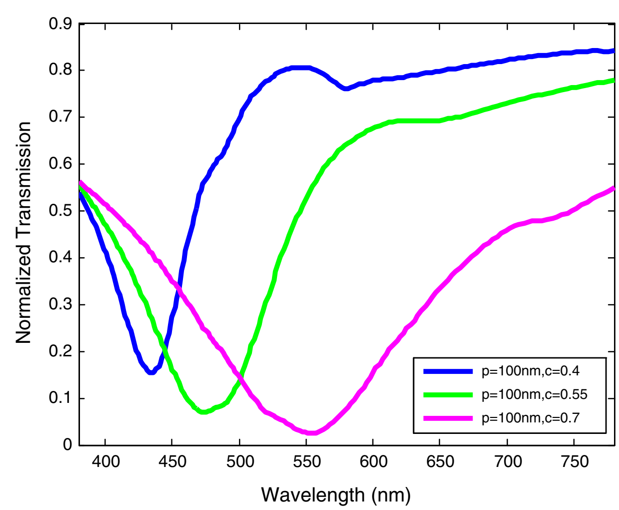

Fig. 2. Transmission spectra of Ag nanogratings with fixed $p = 100$ nm and $d = 15$ nm for different duty cycles. The blue, green and red line represent the transmission spectrum of $c = 0.4$, 0.55, 0.7, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

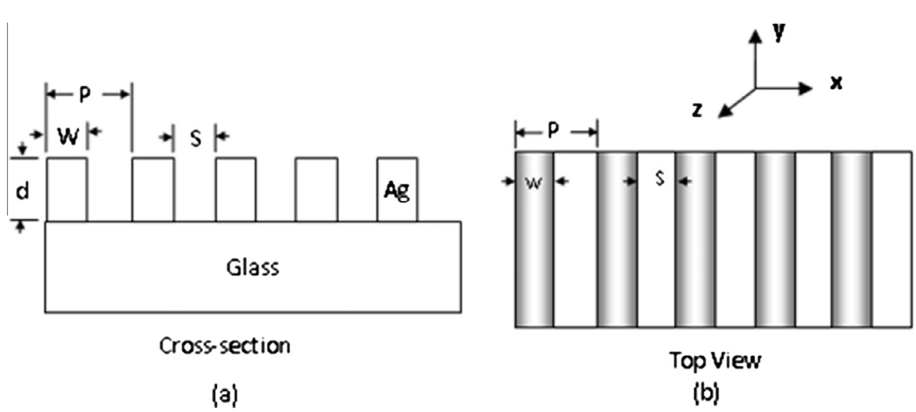

Fig. 1. Illustrations of nanograting structure for metallic Ag film on glass studied here. (a) Cross-section and (b) top view. In this work, we took the duty cycle $c = w/p$, w is the width of the Ag line, s is the width of the slit, d is the thickness of the Ag film, p is the period.