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Design of transmissive quarter-wave plate in the extreme ultraviolet by aperiodic multilayer

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ABSTRACT

Transmissive quarter-wave plates of an aperiodic multilayer structure and with a high throughput in the extreme ultraviolet region are designed based on numerical techniques. Comparing with conventional quarter-wave plates designed by periodic multilayer structures, aperiodic quarter-wave plates show obvious improvement of transmissive output efficiency under the same parameters such as incident angle and photon energy. Besides, transmissive characteristics of quarter-wave plates designed by aperiodic and periodic multilayer structures have been studied, and the optimized parameters for obtaining the highest output efficiency have also been found.

1. Introduction

Nowadays, circularly polarized extreme ultraviolet (EUV) or soft X-ray (SXR) radiations have been used for the study of a wide range of phenomena in chemistry, physics, and material science [1–5] For example, a circularly polarized soft X-ray is suitable for element-specific magnetic imaging based on the X-ray magnetic circular dichroism (XMCD), such as soft X-ray magnetic imaging by Fourier transform holography (FTH) [6,7]. Although generation of circularly polarized light can be achieved in synchrotron radiation source with special insertion devices [8,9], the achievement of quarter-wave plates (QWPs) in EUV or SXR could make it easier by transforming linearly polarized source to circularly polarized radiation directly.

Generally, QWPs are used to control the polarization state of incident light by providing 90° phase shift for its s- and p-polarized components. In the spectral range from near ultraviolet (UV) to near infrared (IR), QWPs can be easily achieved by birefringence crystals. However, it is difficult for the design of efficient QWPS working in EUV or SXR region because most materials are strongly absorbent in such high-energy range.

Nearly 20 years ago, Kortright et al. firstly proposed the idea of realizing polarization conversion of EUV radiation by the periodic multilayer structure (pML) of transmission type, in which large phase shift can be formed between s- and p-polarized components of incident EUV source [10]. After that, design, optimization, and manufacture of QWPs by pMLs have attracted growing attention of scientists. Finally, EUV QWPs fabricated by free standing pMLs have been achieved successfully in laboratory, providing around 10% transmissive output efficiency [11–13].

Due to large absorption of materials for EUV and SXR radiations, the objective of the design of QWPs is to achieve as high throughout as possible by optimizing multilayer structures. Actually, several efforts have been done by Kim et al. and Di Fonzo et al., respectively [14,15]. Their optimizations mainly focused on the choice of material of pMLs. In addition, recent research works on metamaterials also offer a new way for polarization, rotation and conversion of lower frequency electromagnetic waves [16–19].

As a promising optical element in EUV and SXR regions, the aperiodic multilayer structure (aML), which has been successfully applied in ultrafast science [20], EUV lithography [21], plasma spectroscopy [22], and solar physics [23], provides a new way for designing transmissive QWPs with high output. Comparing with pMLs, aMLs could achieve more flexible controls of transmitted spectrum and phase by violating the periodicity of the multilayered structure. Although several broadband phase retarders have been achieved by aMLs already [24,25], designing transmissive QWPs by aMLs have not been explored as far as we know. In this paper, we will explore the possibility of designing transmissive QWPs by aMLs, and evaluate their transmissive characteristics by comparing with QWPs designed by pMLs.

2. Calculation methods

For the design of transmissive QWPs with high output efficiency by aMLs in EUV region, genetic algorithm (GA), which has

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been recognized as a great optimization method and excellent global searching tool for multilayer design [26], is used in our simulation. To evaluate the output efficiency of QWPs quantitatively, the total output efficiency T_v of transmissive QWPs can be defined by the following equation:

$$I{*}T_v = I_s{*}T_s + I_p{*}T_p, \quad (1)$$

where I_s, I_p, and I represent the incident energy of s-polarized component, p-polarized component, and total light. T_s and T_p are the transmittance of multilayer structures for s- and p-polarized components, respectively. In addition, I_s and I_p are determined by the total incident energy I and the azimuthal angle α, which can be described by

$$I_s = I\cos^2\alpha, \quad (2)$$

$$I_p = I\sin^2\alpha. \quad (3)$$

It is well known that, a perfect QWP not only needs to afford 90° phase shift between s- and p-polarized components of incident linearly polarized light, but also has to guarantee nearly the same output for two polarized components. In order to achieve the same output, the azimuthal angle α of incident light should be properly set by

$$\alpha = \arctan\left(\sqrt{\frac{T_s}{T_p}}\right). \quad (4)$$

When Eq. (4) is fulfilled, the output of each polarized component will be equivalent, and the transmitted light will be circularly polarized in the condition that 90° phase difference has been achieved. In this case, the total output efficiency T_v of transmissive QWP can be written as

$$T_v = \frac{2T_sT_p}{T_s + T_p} \quad (5)$$

The merit function (*MF*) of GA, which is used to control the optimization direction, can be defined as follows:

$$MF = \frac{T_v}{(\max(|\Delta\phi - 90^\circ|, \varepsilon))^2}, \quad (6)$$

where $\Delta\phi = |\phi_s - \phi_p|$ denotes the phase difference between transmitted s- and p-polarized components (ϕ_s and ϕ_p are phases of transmitted s- and p-polarized components, respectively). A small tolerance parameter ε is added to increase the convergence speed without over-emphasizing a perfect 90 degree phase difference. In our calculation, we set ε to 1°. The square factor in the denominator aims to increase the weight of phase delay in the *MF*, and then improve the searching efficiency of GA. By maximizing the merit function shown in Eq. (6), we can find out the optimized aMLs for achieving transmissive QWPs with high output efficiency.

In our simulation, free standing aperiodic Mo/Si multilayer structures, shown in Fig. 1, have been chosen for transmissive QWPs design, due to their great performance of controlling phase and spectrum in EUV region over the years. Transfer-matrix method (TMM) [27,28] has been used to calculate the transmission coefficient of aMLs. Also, the optical constants of Si and Mo used in our calculation were taken from Ref. [29], e.g. 0.9975+0.0019i and 0.9193+0.007i for Si and Mo at 90 eV. Furthermore, the inter-diffusion effect between Mo and Si layers in multilayer structure has been considered in all cases following the proven model used in a realistic design of aperiodic Mo/Si multilayer [30].

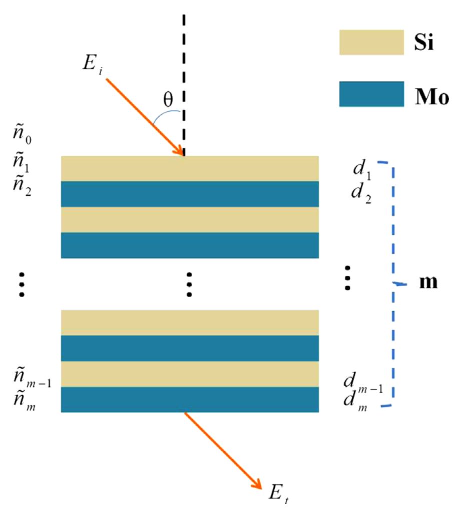

Fig. 1. Schematic of aperiodic Mo/Si mutliayer structure.

3. Numerical calculation results and analysis

In this section, QWPs of transmissive type are designed by aperiodic Mo/Si multilayer structures in EUV region, by means of genetic algorithm described above. After enough generation, GA simulation will give out the optimized aML structure for transmissive QWP design.

By using a DC magnetron sputtering system, an average deposition rate of several angstrom/sec can be realized for Mo and Si under 1×10^{-7} Torr base pressure and 1 mTorr Ar gas pressure, making it easy for nanometer thin film deposition. Also, the thickness error of the layer can be controlled within 1% of the desired thickness in this case [30]. So, searching range of thickness for each layer in aML is from 2 to 15 nm in our simulation.

With GA simulation, a transmissive QWP working at 90 eV (E=90 eV) and 45° incident angle (θ=45°) has been designed successfully by an aperiodic Mo/Si multilayer. Transmissive characteristics (T_v and $\Delta\phi$) and thickness distribution of this aML are

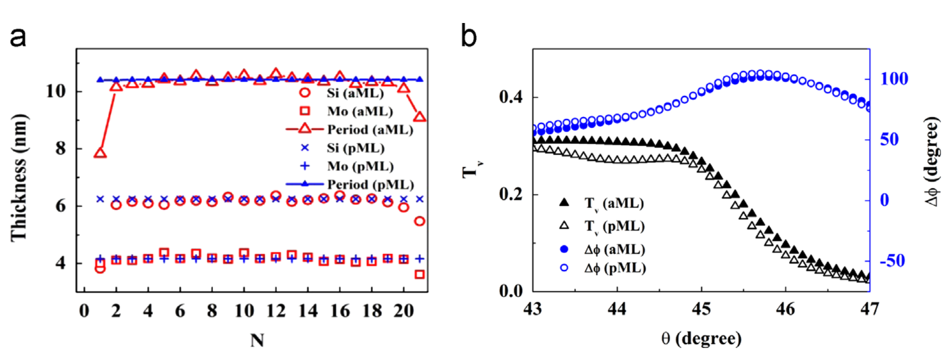

Fig. 2. (a) Thickness distribution of aML and pML respectively, (b) T_v (triangle) and $\Delta\phi$ (circle) of QWPs designed by aML (solid symbol) and pML (open symbol) versus incident angles (from 43° to 47°).