Chapter 42
Multilayer Mirrors for Focusing Objective in 40-nm Wavelength Region

M. Toyoda, Y. Tamaru, S. Mori, K. Sawada, Y. Fu, E. J. Takahashi, A. Suda, F. Kannari, K. Midorikawa and M. Yanagihara

Abstract Isolated attosecond pulse (IAP) generation with pulse energy of a few μJ has been reported in the 40-nm wavelength region. For diffraction-limited focusing on the IAP, we are developing a Schwarzschild objective made of two-curved multilayer mirrors. To generate intense light fields with a maximum intensity of over 10^{16} W/cm^2 on the objective focus, we designed, fabricated, and tested multilayer mirrors for practical high reflectivity in the 40-nm wavelength region.

42.1 Introduction

Recently, isolated attosecond pulse (IAP) generation in the 40-nm wavelength region has been reported: an isolated intense pulse with pulse energy of a few μJ was demonstrated using a novel two-color gating method [1]. When an attosecond high-power extreme ultraviolet (EUV) pulse is focused using a diffraction-limited objective to produce a small focal spot with a diameter of a few handled nanometers, it is possible to generate extremely intense fields with a maximum intensity of over 10^{16} W/cm^2, thereby opening a new frontier of nonlinear optics. For the diffraction-limited focusing of the IAP, we are developing a Schwarzschild objective made of two-curved multilayer mirrors [2, 3]. This objective has two practical advantages: high spatial resolution resulting from the large numerical aperture optical design and spectral selectivity based on the Bragg reflection of

M. Toyoda (✉) · S. Mori · M. Yanagihara
Center for Advanced Microscopy and Spectroscopy, IMRAM, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan
e-mail: toyoda@tagen.tohoku.ac.jp

Y. Tamaru · K. Sawada · Y. Fu · E. J. Takahashi · K. Midorikawa
RIKEN Center for Advanced Photonics, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Y. Tamaru · A. Suda
Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan

K. Sawada · F. Kannari
Keio University, Yokohama 233-8522, Japan

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multilayer mirrors. Producing this objective requires multilayer mirrors with practical high reflectivity. In this paper, we describe the design, fabrication, and testing of multilayer mirrors that are suitable for focusing in the 40-nm wavelength region.

42.2 Optical Design

To realize high reflectivity on multilayer mirrors, we applied the selection criterion for a coating material pair given by Yamamoto et al. [4]. According to the criterion, we expected high reflectivity from a material pair with both low absorption and a large Fresnel reflection coefficient at the interface, which corresponds to a large distance between the two materials on the complex plane plot of optical constants. After considering the criterion and availability of sputter targets, we chose several material pairs for the trial mirrors, as shown in Table 42.1. The period and thickness ratio of the mirrors were numerically optimized with IMD software [5] to give the maximum reflectivity at a wavelength of 40 nm.

Optical designs and calculated maximum reflectivity values for normal incident rays at a wavelength of 40 nm are tabulated in Table 42.1. We expected relativity high reflectivity from mirrors with an Mg spacer layer, while Si-based mirrors were expected to yield moderate reflectivity. For high reflectivity, the thickness of non-spacer layers, e.g., Mo, Cr, B_4C, and SiC, should be reduced, because the absorption of these materials is relatively large.

42.3 Experimental Results

The six trial mirrors in Table 42.1 were sputter deposited on Si wafers using a magnetron sputtering apparatus (SPL-500, Anelva Corp.) at Tohoku University. The period was examined with small-angle X-ray diffraction (XRD) and controlled by adjusting deposition time. We precisely controlled the period within 0.2 nm of the design values on Table 42.1. At-wavelength reflectivity was then measured with two different methods. First, we applied a reflectometer based on the higher

Table 42.1 Optical designs obtained with the numerical optimization procedure

Material	Period (nm)	Thickness ratio	Reflectivity
Mo/Mg	21.2	0.25	0.59
Cr/Mg	21.2	0.23	0.57
B_4C/Mg	21.2	0.25	0.54
SiC/Mg	21.2	0.25	0.53
Mo/Si	23.8	0.36	0.37
Sc/Si	21.0	0.33	0.31

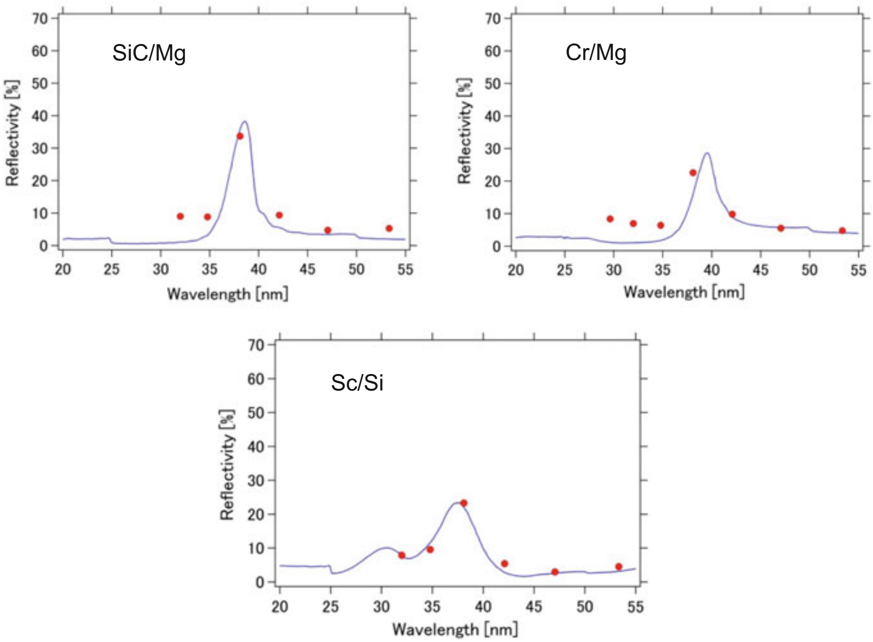

Fig. 42.1 Spectral reflectivity of trial mirrors. Solid curves and symbols represent data measured with synchrotron light and higher harmonics, respectively

harmonics of a Ti-sapphire laser at Riken. Symbols in Fig. 42.1 represent reflectivity for the higher harmonics at an incidence angle of 2°. We confirmed relatively high reflectivity (over 0.2) for the SiC/Mg, Cr/Mg, and Sc/Si multilayer mirrors. For the other samples, we observed reflectivity values less than half of those calculated. These degradations likely arose from the roughness due to heavy diffusion at the interface of the multilayer mirrors.

Finally, spectral reflectivity was confirmed by applying an EUV reflectometer equipped on the beamline BL5B of UVSOR at the Institute for Molecular Science. To suppress second- and higher-order lights from the monochromator, we applied a 300-nm thick Mg filter upstream of the reflectometer. The solid curves in Fig. 42.1 represent measured reflectivity as a function of wavelength. For reference, reflectivity data measured with the higher harmonics are indicated with symbols. The incident angle of the EUV rays on the trial mirrors was 11°. We confirmed that the results from the two different reflectometers were in good agreement. Relativity high reflectivity (over 30%) was achieved for the Mg-based multilayer mirrors. The reflectivity of the SiC/Mg multilayer mirror reached a practical level (40%) over a wide bandwidth. The results indicate that, when the IAP is focused without aberrations, a maximum intensity of over 10^{16} W/cm^2 can be expected at the focus of a two-bounce objective consisting of SiC/Mg multilayer mirrors.

42.4 Summary

Multilayer mirrors were developed for a focusing objective in the 40-nm wavelength region. For high reflectivity, we applied a selection criterion based on wave optics theory and chose six material pairs. Trial mirrors were then fabricated and tested. We successfully confirmed a practically high reflectivity (40%) and wide bandwidth for the SiC/Mg multilayer mirror. Group delay is also important for ultrafast optics because it modulates pulse duration on the focus. This aspect will be examined in future work.

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