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A compact, intense, monochromatic, atmospheric pressure, extreme ultraviolet light source

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An intense, monochromatic, extreme ultraviolet (121.6 nm) light source has been constructed for testing extreme ultraviolet light rejecting filters. The source and detection system operates at atmospheric pressure, is physically compact, and is relatively inexpensive to build. A calibrated neutral density filter with a transmission of 1×10^{-6} is used as a reference. The light source has been used to measure transmissions as small as 9×10^{-6} quickly (in less than 1 min) with negligible background levels. © *1998 American Institute of Physics.* [S0034-6748(98)04204-X]

I. INTRODUCTION

In this article, we describe a compact, intense, monochromatic, extreme ultraviolet light source that operates at atmospheric pressure. The source was developed to measure the ultraviolet transmission of free-standing, submicron period, gold, transmission gratings[1] that will be used to detect and image neutral atom emission from the earth's magnetosphere while simultaneously rejecting background ultraviolet light.[2,3] The wavelength of interest is 121.6 nm, the Lyman alpha line of hydrogen, and the gratings are designed to function as waveguides above cutoff for 121.6 nm light.[4] The grating periods are 200 nm, with nominal 50 nm slots and 150 nm bars. The gratings range in thickness from 400 to 600 nm and are manufactured by the Nanotechnology Center at the Massachusetts Institute of Technology.[1,5] Previous calculations and measurements[4,6,7] indicate that the transmission level for these gratings is in the range of 10^{-4} to 10^{-6}.

Testing these gratings quickly, accurately, and consistently, requires an intense, monochromatic, extreme ultraviolet light source. There are two standard techniques for generating monochromatic 121.6 nm light for such testing purposes: a gas discharge coupled to a vacuum ultraviolet, grazing incidence monochromator;[8] or a synchrotron light source.[6,7] Both of these techniques require an extensive vacuum system and costly ancillary equipment. In addition, the grazing-incidence-monochromator approach results in insufficient signal through a grating with a transmission coefficient of 10^{-6}. Because the light source does not have to be highly monochromatic [a source with a full width at half maximum (FWHM) of a few nanometers is sufficient] it is possible to trade light source monochromaticity for ease of operation from compact light source. We describe the unique features of a new light source and present initial grating measurements along with theoretical predictions to demonstrate the operation of the light source. The source functions as designed has proved capable of measuring the transmission of 121.6 nm light through the free-standing gratings at levels as small as 10^{-6}.

II. LIGHT SOURCE DESCRIPTION

The essential components of the light source are a 30 W Hamamatsu deuterium lamp with primary emission in the range 120–200 nm, two 10 nm FWHM bandpass filters with a central wavelength of 121.6 nm, an ultraviolet to visible conversion phosphor, and a high sensitivity photomultiplier tube detector as depicted in Fig. 1. The convolution of the measured deuterium lamp spectrum and the measured bandpass filter transmission characteristics in the extreme ultraviolet is shown in Fig. 2. The deuterium lamp was constructed with a magnesium fluoride window to permit emission of 121.6 nm light. As shown in Fig. 2, the filtered lamp spectrum has a FWHM of roughly 2.5 nm, centered at 121.6 nm. The lamp also emits strongly in the visible and a second bandpass filter was required to improve the ratio of ultraviolet to visible light to 10^5.

After passing through the bandpass filter, the extreme ultraviolet light passes through a shutter mechanism and illuminates a sliding mount that holds one free-standing grating and a calibrated neutral density filter (transmission coefficient$=1.4\times10^{-6}$ at 121.6 nm). Behind the sliding mount is a glass blank coated with approximately 1 mg/cm^2 of phosphorescent sodium salycilate. At that thickness, the sodium salycilate phosphor converts 120 nm ultraviolet light to visible 420 nm light with a quantum efficiency of approximately 80%.[9] Visible inspection of the phosphor coated blank indicates that it is uniformly illuminated by the light source. Behind the glass blank is a Hamamatsu R6905 photomultiplier detector with a gain of approximately 2×10^7 when biased with 1300 V. The peak of the photomultiplier spectral response is centered at 420 nm. Since the photomultiplier tube is a sealed unit, there is no need for a vacuum system for the photon detection system.

The entire apparatus is enclosed in an aluminum housing through which a continuous purge of 99.99% helium gas flows. Helium has no absorption lines near 121.6 nm. Operation in a helium atmosphere greatly reduces the absorption of extreme ultraviolet light by water vapor, oxygen, and nitrogen molecules; thereby eliminating the need to place the filters and gratings in a vacuum system. For cleanliness purposes, the aluminum enclosure is housed in a sealed glove

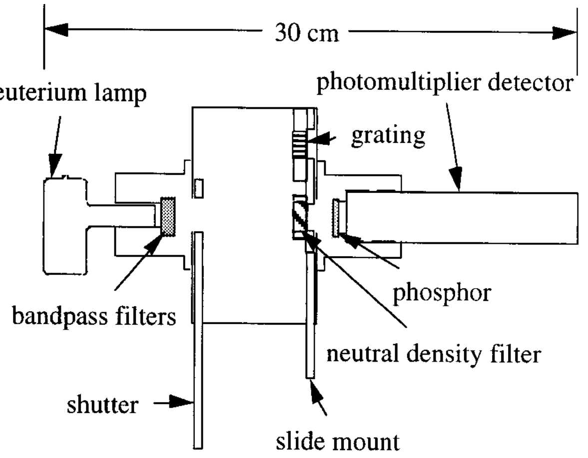

FIG. 1. The compact 121.6 nm light source.

box. The glove box helps to reduce contamination of the free-standing gratings by dust and water vapor.

Considerable care has been taken to eliminate background light in the apparatus. The sliding mount and shutter mechanisms include a sliding o-ring slide for blocking light from going around the shutter and test objects. The bandpass filters, sodium salycilate phosphor, and photomultiplier are also mounted in the apparatus with o-ring seals. The measured background light due to external sources and from light leaking around the grating or neutral density filter mounts contributes less than 1% to the transmission measurements reported in the following section. If reduced signals levels are acceptable, the light source can be operated without the helium purge. Signal levels are reduced by more than an order of magnitude, but the background light effects remain ignorable. As mentioned previously, the visible contribution to the total photon flux after the bandpass filters is 1 part in 10^5. Because the typical grating transmission in the visible is 1000 times larger than the transmission in the extreme ultraviolet (a skin depth effect), the visible light contribution to the total grating transmission measurements is roughly 1%.

For spatially localized measurements of the grating transmission across the entire grating surface, a collimator can be inserted into the shutter aperture. The collimator illuminates a 2-mm-diameter region on the grating or the reference neutral density filter.

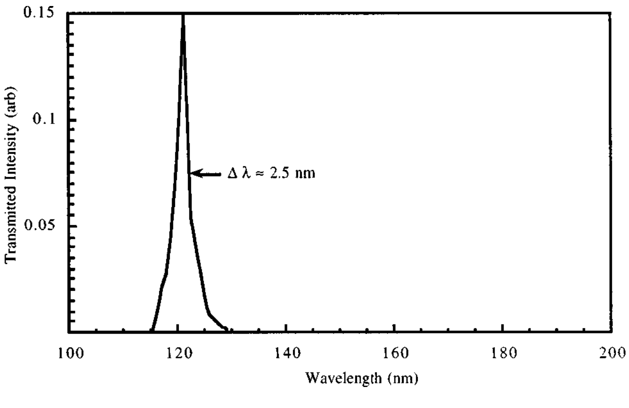

FIG. 2. Convolution of the measured deuterium lamp spectrum with the measured transmission characteristics of the bandpass filter in the extreme ultraviolet.

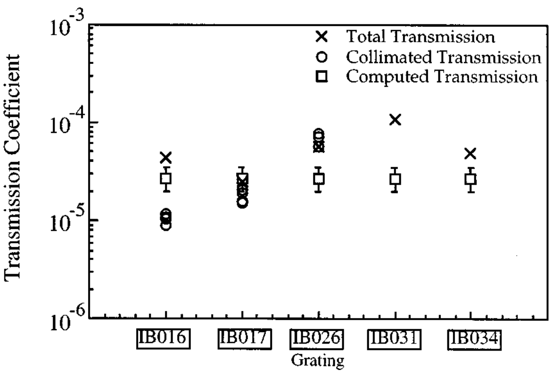

FIG. 3. Experimental measurements of the 121.6 nm transmission through five gold gratings are denoted by open circles and X's. The X's represent the transmission coefficient when the entire grating surface is illuminated. The open circles are the transmission coefficient for a small region (approximately 2 mm in diameter) of the grating. The computational predictions are indicated with open squares.

III. TRANSMISSION MEASUREMENTS

As the design goal of this light source was to be able to produce monochromatic, extreme ultraviolet light which is intense enough to provide rapid measurements of transmission levels as small as 10^{-6}, we show in Fig. 3 the measured transmission through five free-standing gratings supplied by the MIT group. The transmissions are measured by comparing the free-standing grating transmission to the transmission through the calibrated neutral density filter at a number of different photomultiplier detector biases and helium purge gas flow levels. In some cases, the measurements represent a total grating transmission measurement. In other cases, the measurements were performed using the collimator and are measurements of the transmission in a spatially localized portion of the grating. Background light levels subtracted from the free-standing grating and neutral density filter measurements were obtained with the shutter mechanism closed and were ignorable.

The predicted transmissions for each grating are represented by solid squares in Fig. 3. The predictions are from computational calculations using a full three-dimensional rigorous coupled-wave analysis algorithm.[10] Convergence of the TM polarization case, usually a problem with these types of algorithms, has been enhanced with a Fourier coefficient balancing technique.[10] The three-dimensional structure of the grating was obtained by cleaving a typical photoresist layer and measuring, by scanning electron microscopy (SEM), the pattern etched into the photoresist material before plating. Therefore, the computational results represent an average grating structure in terms of slot width and bar shape. The measurements are generally consistent with the predictions. The higher transmissions are due to pinholes and other structural problems with the gratings (seen in SEM images). The lower transmissions are due to narrower grating slots then were assumed in the computational model—a result of over etching the photoresist.

IV. DISCUSSION

The apparatus functioned as intended and provided an intense source of monochromatic, extreme ultraviolet light without requiring an extensive vacuum system, or delicate microchannel plate detectors. Grating transmissions were measured down to the 10^{-6} level, and 10^{-7} level measurements appear achievable. Simply by changing the bandpass filter, the same apparatus can be used to generate intense, monochromatic radiation from 120 to 200 nm. The entire apparatus cost less than $7000 to construct.

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