Optical characterizations and thermal analyses of HfO$_2$/SiO$_2$ multilayered diffraction gratings for high-power continuous wave laser

Inki Kim$^{1,5}$, Sunae So$^{1,5}$, Jungho Mun$^{2,5}$, Kwang Hyun Lee$^1$, Jung Hwan Lee$^1$, Taejun Lee$^3$ and Junsuk Rho$^{1,2,4}$

$^1$ Department of Mechanical Engineering, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea
$^2$ Department of Chemical Engineering, Pohang University of Science and Technology (POSTECH), Pohang 37673, Republic of Korea
$^3$ Agency for Defense Development (ADD), Daejeon 34186, Republic of Korea
$^4$ National Institute of Nanomaterials Technology (NINT), Pohang 37673, Republic of Korea
$^5$ These authors contributed equally to this work

E-mail: jsrho@postech.ac.kr

Keywords: diffraction grating, high power laser, spectral beam combining, dielectric multilayer

Abstract

Spectral beam combining technique is a simple and straightforward method to obtain a high-power laser beam. The beam combining system typically consists of three parts: fiber laser array, transform optical system and diffraction grating. Performance of the system (diffraction efficiency and laser induced damage threshold) is mainly determined by the diffraction grating. This paper describes a multilayer dielectric diffraction gating with high diffraction efficiency and low laser-induced damage threshold, which can be potentially used to obtain a high-power laser by combining laser beams. The diffraction grating is designed by coupled-wave analysis, and single-beam laser interference lithography is used to fabricate diffraction gratings. To verify the optical and thermal characteristics of the beam, we measure diffraction efficiency and the threshold for laser-induced damage. Finite element method simulation accurately represented temperature distribution in the grating during laser irradiation. This work provides integrated methods that include design of multilayer dielectric gratings, thermal analysis and device characterization using high-power laser.

1. Introduction

A diffraction grating with a high diffraction efficiency and thermal robustness is in great demand for high-power laser beam generating systems such as chirped-pulse amplification [1, 2] and spectral beam combining applications [3–6]. Hence, so far many studies have been conducted to realize a diffraction grating exhibiting a high diffraction efficiency and laser induced damage threshold (LIDT). To realize high diffraction efficiency with thin layers, metallic gratings [7–10] were frequently used due to their high reflectivity characteristics, but unfortunately low LIDT value [9] from high light absorption in a metal was troublesome. In contrast, those two desirable characteristics can be achieved simultaneously by using multilayer dielectric gratings (MLDG), in which dielectric thin layers that have low and high refractive indices are stacked alternately [11–15]; precisely machined grating patterns on the uppermost layer can yield high diffraction efficiency. However, the diffraction efficiency of MLDGs is affected by several parameters such as the number of multilayers, the thickness of each layer, and grating width or height, so to produce highly efficient gratings the combination of these parameters must be optimized [14, 16].

LIDT is affected by many factors [15, 17–23], including the confined electric field effect [15], and the mechanical or optical properties of thin films [23] such as refractive index or absorption coefficient. Particularly the process of cleaning the MLDG is important because defects or contamination can induce a confined electric field and thus severely degrade LIDT [23–26]. Most assessments of LIDT have been conducted experimentally by measuring wavefront distortion or local temperature during or immediately
after laser irradiation, and by direct structural observation using scanning electron microscopy [15, 20, 21]. However, few thermal simulation studies have been conducted to estimate LIDT or temperature elevation [27, 28].

Here, we propose a method to produce thermally robust MLDGs with high diffraction efficiency and high LIDT working for high-power continuous wave (CW) laser. First, to optimize various parameters we used rigorous coupled-wave analysis (RCWA) and finite difference time domain (FDTD) simulations to visualize the electric field distribution of MLDG simultaneously. Then we fabricated the designed MLDG device on a fused silica substrate by using single beam laser interference lithography (LIL) on an area of 30 mm × 30 mm. We used a very thick (20 mm) fused silica substrate to carefully verify the LIDT of the MLDG device itself, suppressing the effect of substrate absorption [29, 30]. To verify the optical and thermal characteristics, we measure diffraction efficiency and LIDT under illumination from a high-power CW laser.

We also propose a systematical thermal analysis approach based on microscopic electromagnetic simulations. Furthermore, we suggest multiphysics finite element method (FEM) simulation of microscopic electric field and macroscopic temperature distribution to analyze thermal characteristics during experimental observation of temperature elevation. The simulated temperature distribution and corresponding thermal deformation can provide feedback for designing an optically and thermally robust MLDG device. The proposed systematic methods that include design/fabrication of multilayer dielectric gratings, thermal analysis and device characterization using a high-power laser will pave a way to designing optically and thermally robust diffraction gratings.

2. Results

2.1. Optimizing and designing multilayer dielectric gratings

We used RCWA to efficiently calculate diffraction efficiency from grating on a dielectric multilayer [31, 32]. RCWA allows fast and efficient calculation of diffraction efficiency from grating on a dielectric multilayer structure and therefore was used for the optimization process in this work. The incident and transmitted fields of the system and the fields inside the system are Fourier-decomposed according to the Floquet–Bloch theorem, and the fields are related by the boundary condition, then the coefficients are solved in matrix form. The codes were confirmed by comparing with results from numerical simulations in FDTD (Lumerical FDTD) and FEM (COMSOL Multiphysics). The simulation considered several variables (table 1).

Table 1. Parameters and their corresponding abbreviations and values. Some expressions are dependent on others: $\Lambda = 1/\rho_f$, $w_g = f\Lambda$, $w_s = (1 - f)\Lambda$, $\theta_1 = \sin(\lambda_0/\Lambda/2)$.

| Parameter                  | Abbreviation | Value  |
|----------------------------|--------------|--------|
| Grating density            | $\rho_f$     | 1740 mm$^{-1}$ |
| Duty cycle                 | $f$          | 0.3    |
| Incident angle             | $\theta$     | 67.77$^\circ$ |
| SiO$_2$ thickness          | $t_1$        | 247 nm |
| HfO$_2$ thickness          | $t_2$        | 163 nm |
| Grating thickness          | $t_g$        | 630 nm |
| Matched-layer thickness    | $t_m$        | 450 nm |
| Number of multilayers      | $N_1$        | 20     |
| Incident wavelength        | $\lambda_0$  | 1064 nm |
| Periodicity                | $\Lambda$    | 575 nm |
| Grating width              | $w_g$        | 172.41 nm |
| Spacing width              | $w_s$        | 402.30 nm |
| SiO$_2$ refractive index   | $n_1$        | 1.44   |
| HfO$_2$ refractive index   | $n_2$        | 1.87   |
| Littrow angle              | $\theta_1$   | 67.77$^\circ$ |

Particularly, the optical properties of the hafnium oxide layer varies depending on a growing method and corresponding process conditions. In our experiment, we used amorphous state-hafnium oxide deposited by general e-beam evaporation method, whose measured refractive index at 1064 nm wavelength is 1.87 (1.44 for silicon dioxide). The multilayer combination of hafnium oxide and silicon dioxide index are confirmed to be appropriate to achieve high reflectance in the required wavelength regime from 1040 to 1080 nm as described in the following simulation.

MLDG considers $\rho_f, f, w_g, t_g, t_m, \theta_1, t_1, t_2$, and $\theta_1$, so optimization is desirable to efficiently acquire a MLDG design that has maximized figure-of-merit ($R_{-1}$; reflection of the $-1$st order diffraction beam) at $\lambda_0$, and TE polarization. Several solutions give $R_{-1} \approx 1$, so we do not directly maximize $R_{-1}$. We tried to find a method that is tolerant to fabrication and working conditions, and to limit the number of variables as much as possible to simplify the optimization process. $\lambda_0 = 1064$ nm was fixed, and the grating periodicity $\Lambda$ was
Figure 1. Optimization process of multilayer and grating. 2D mapping of $R_{-1}$ varying (a) multilayer (b) grating parameters to find optimal MLDG condition with high robustness and tolerance for fabrication. (c)–(e) Robustness of diffraction efficiency against (c) incident wavelength, (d) incident angle, and (e) incident polarization error. $\phi$ is the angle between grating vector and the plane-of-incidence; $\psi$ is the angle between electric field and the plane-of-incidence (i.e. $\psi = 90^\circ$ for TM and $\psi = 0^\circ$ for TE).

Figure 2. Optimized MLDG schematics. (a) Parameters description and (b) corresponding diffraction efficiency 2D plot against wavelength and incident angle.

determined as $\Lambda = 1/\rho_g = 575$ nm. The incident angle $\theta$ was fixed at the Littrow angle $\theta_L = \arcsin(\lambda_0/\Lambda/2)$, at which the incident wavevector and the reflected wavevector in $-1$ order diffraction lie on the same line.

We first maximized reflection $R$ from the multilayer by changing $t_1$, $t_2$, $N_L$ at fixed $\theta = \theta_L = 67.77^\circ$ that had been determined from our target $\Lambda$. Increase in $N_L$ increases $R$ but also increases fabrication effort, so we chose $N_L = 20$. Solutions with high $R$ periodically appear (figure 1(a)), but we chose the first solution of
Device fabrication using laser interference lithography. (a) Optical setup for single beam laser interference lithography. (b) Image of thick fused silica substrate on which grating structures are fabricated. (c) SEM image of fabricated grating structures. Scale bar: 500 nm.

$t_1 = 247$ nm and $t_2 = 163$ nm to minimize the multilayer deposition process while maintaining large fabrication tolerance. Grating was added on top of the optimized multilayer and optimized for $t_m$, $t_g$, and $f$. Reduction in $f$ increases fabrication tolerance with large $R_{-1}$, but fabrication may become too difficult if $f$ is too small so we chose $f = 0.3$. Again, solutions with high $R_{-1}$ appear periodically (figure 1(b)); we chose $t_m = 450$ nm and $t_g = 630$ nm to compromise between high $R_{-1}$ and fabrication tolerance. Finally, we checked how diffraction efficiency is affected by changes in $\lambda$ (figure 1(c)), $\theta$ (figure 1(d)), and polarization error (figure 1(e)). $R_{-1}$ remained $>0.95$ at $1050 < \lambda < 1070$ nm and $64 < \theta < 70^\circ$, and at polarization error $<5^\circ$. The final device configuration and the corresponding diffraction efficiency against incident angle are shown in figure 2.

2.2. Fabrication of multilayer dielectric gratings by laser interference lithography

We used a single-beam LIL system (figure 3(a)) to generate grating patterns in on the fused silica substrate. We used a He–Cd laser with wavelength 325 nm, and used a Lloyd’s mirror to set up the interference system. The parameters of gratings such as line width, pitch and duty cycle are determined by laser power, incident angle or development condition. We fabricated grating patterns with pitch of 574 nm and duty cycle of 0.3. First, a negative photoresist (PR, AZ nLOF 2020) was spin-coated on $35 \times 35 \times 20$ mm multilayer-coated fused silica substrate at 2000 rpm for 40 s to form a PR layer $\sim 300$ nm thick. Then the PR spin-coated substrate was soft-baked at 130 °C for 10 min on a hot plate; this baking time was optimized for the substrate thickness of 20 mm. After soft baking, the substrate was exposed for 6 s in the LIL setup then baked at 135 °C for 10 min on a hot plate. To develop the substrate, it was immersed in a developer for 85 s, then rinsed with de-ionized water and dried with N$_2$ gas. This process yielded a PR line pattern with 575 nm pitch and...
400 nm width. After development, a Cr line pattern with 40 nm thickness was made using a lift-off method. Finally, reactive ion etching using a dielectric ICP etcher was used to transfer the Cr pattern to the top layer of the multilayer. The SiO$_2$ layer was etched using CF$_4$ (20 sccm), CHF$_3$ (40 sccm), O$_2$ (10 sccm), Ar (5 sccm) gas, then the Cr was removed using Cr etchant. The resultant MLDG had 575 nm pitch and 172 nm width (figures 3(b) and (c)).

2.3. Optical and thermal characterization of multilayer dielectric gratings

We measured diffraction efficiency and LIDT of the fabricated MLDG using high-power CW laser (YLS 1000-SM, IPG Photonics). As an input laser we used a 40 mW fiber laser with 1064 nm wavelength and TE polarization (figures 4(a) and (b)). We placed the MLDG at $\theta_L \approx 67^\circ$, and measured the power of the diffracted $-1$st beam. The diffraction efficiency was measured at three different areas (figure 4(c)). Average efficiency was $\sim$80% and maximum efficiency was $\sim$85.5% at $\theta_L = 64^\circ$ (table 2). The reduced efficiency is caused by geometry variations during the fabrication imperfections. First, we have beam stability issue in the laser interference lithography process. In this work, we set up a single beam interference lithography system, and due to the Gaussian beam profile of the single beam, the edges are irradiated with a relatively weak intensity of light, which results in poor patterning. Secondly, in this study, since a very thick substrate with a thickness of 20 mm is used, the degree of heat loss varies in each substrate region. As a result, the etching rate in each region is changed, and the etching depth, which greatly affects the diffraction efficiency, is changed. For these reasons, the diffraction efficiency is little bit deviated from the simulation result. Particularly, the width and depth of the grating is critical for diffraction efficiency, and the pitch of grating effects at $\theta_L$.

Table 2. Laser irradiation spot and experimental data at input power of 40 mW. Efficiency is defined as ratio of $-1$st diffracted beam power to input beam power.

| Irradiation spot | Output power (mW) | Efficiency (%) | $\theta_L$ |
|------------------|-------------------|----------------|-----------|
| 1                | 31.8              | 79.50          |           |
| 2                | 34.2              | 85.50          | $\sim$64^\circ |
| 3                | 31.4              | 78.50          |           |
Figure 5. Laser-induced damage threshold measurement. (a) Optical setup for laser-induced damage threshold measurement. (b) Image of the device under laser irradiation. Bright spot: irradiating laser beam. (c) Thermal image (temperature distribution) of the device during laser irradiation.

Table 3. Experimental temperature variation data.

| Laser power (W) | Temperature (°C) |
|-----------------|------------------|
|                 | Initial | Final | Rise |
| 200             | 22.8    | 23.0  | 0.2  |
| 400             | 22.7    | 23.5  | 0.8  |
| 600             | 23.4    | 24.8  | 1.4  |
| 800             | 23.7    | 26.1  | 2.4  |
| 1000            | 23.9    | 26.7  | 2.8  |

LIDT was then measured by comparing the diffraction efficiency before and after laser irradiation of a region (figure 5(a)). The high-power laser with random polarization is used to measure LIDT and 40 mW power laser with 1064 nm wavelength (single frequency) and TE polarization is used to measure diffraction efficiency. The procedure is as follows. First the high-power laser is irradiated to the diffraction grating for about 60 s to measure the temperature change. Thereafter, the high-power laser is turned off and the 40 mW power laser is irradiated to the same position to measure the diffraction efficiency. We used a thermal camera to measure the temperature in real time (figures 5(b) and (c)). To achieve laser damage we used power up to 1 kW (5 kW cm$^{-2}$ on the grating surface); after irradiation, the temperature increased by ~2.8 °C and diffraction efficiency was unchanged (table 3). The diffraction efficiency was measured after laser irradiation and measured power for the −1st order is 33.4 mW indicating 83.5% efficiency.

2.4. Thermal analysis and simulations
We also conducted thermal analysis via FEM-based numerical simulation. We proposed systematical approach of thermal analysis based on microscopic electromagnetic simulation. The thermal analysis was
Figure 6. Thermal analysis results. (a) Strategy of thermal analysis and results after laser irradiation for 60 s. Thermal analysis is performed by obtaining (1) microscopic electric field, (2) heat sources and (3) macroscopic temperature distribution. (b) Maximum temperature of the structure for different time. (c) Maximum rising temperature according to the incident laser power. Red squares indicate experimental results. The upper and lower boundary of the shaded region indicate simulation results of $h = 5 \text{W m}^{-1} \text{K}^{-1}$ and 100 \text{W m}^{-1} \text{K}^{-1}$, respectively. The blue dotted line indicates the simulation results of $h = 30 \text{W m}^{-1} \text{K}^{-1}$. (d) Macroscopic displacement distribution due to the temperature variation after 60 s irradiation.

Table 4. Bulk material properties used for the thermal analysis.

| Parameters                        | SiO$_2$ | HfO$_2$ | Substrate |
|----------------------------------|---------|---------|-----------|
| Extinction coefficient, $\kappa$ ($\times 10^{-6}$) | 4.6     | 7       | 4.6       |
| Density, $\rho$ (kg m$^{-3}$)    | 2100    | 9700    | 2200      |
| Heat capacity at constant pressure, $C_p$ (J kg$^{-1}$ K$^{-1}$) | 730     | 120     | 670       |
| Thermal conductivity, $k$ (W m$^{-1}$ K$^{-1}$) | 7.6     | 0.6     | 1.4       |
| Thermal expansion (1/K)          | $6 \times 10^{-6}$ | $6 \times 10^{-7}$ | $5.5 \times 10^{-6}$ |
| Young’s modulus [GPa]            | 70      | 57      | 72        |
| Poisson’s ratio                  | 0.18    | 0.2     | 0.17      |

performed in three steps (figure 6(a)). At first, we calculated the electric field induced by the incident laser on the microscopic structure of the grating in the central region of the Gaussian beam. Although the cross section of the incident laser beam has a Gaussian power profile, it can be regarded as a plane wave within a single grating period, so a Floquet periodic boundary condition was applied. Then the electric field distribution is used to obtain an energy dissipation $Q$:

$$Q = \langle J \cdot E \rangle = \sigma |E|^2 = \frac{\varepsilon_0 \varepsilon \omega}{\mu_r} |E|^2$$

where $J$ is current density, $E$ is electric field, $\varepsilon$ is real part of refractive index, $k$ is extinction coefficient (imaginary part of refractive index), $\varepsilon_0$ is permittivity of vacuum, $\omega$ is frequency, and $\mu_r$ is relative permeability. $Q$ functions as a heat source. Finally, the microscopic energy dissipation was averaged per unit volume and introduced as volume heat sources in a macroscopic simulation that considers a real sample size of $35 \times 35 \times 20$ mm. In macroscopic thermal calculation, MLDG structures are approximated as a uniform single-layer, where the average heat sources are applied with a Gaussian distribution with a beam radius of 5 mm. The physical properties used in the thermal analysis are described in table 4. All surfaces of the whole structure are subjected to a natural convection boundary condition with air that has an ambient temperature of 20 $^\circ$C and heat transfer coefficient ($h$) of 30 W m$^{-1}$ K$^{-1}$. After laser irradiation at 1 kW for 60 s, the
average heat source per volume for the MLDG structure was 0.541 kW cm$^{-3}$, and the maximum temperature was 27.5 °C (3.6 °C rise) (figures 6(a) and (b)). The temperature distribution follows the same Gaussian distribution as the heat sources that were used. The differences between the simulated (3.6 °C) and experimentally measured (2.8 °C) rising temperatures are mainly caused by $h$, which is difficult to be controlled under experiments. A typical value of $h$ in air is in the range of 5–100 W m$^{-1}$ K$^{-1}$ for natural convection. Therefore, the maximum rising temperatures with respect to laser powers are calculated within the range of $h = 5–100$ W m$^{-1}$ K$^{-1}$ (figure 6(c)). The results show that simulation results agree with the experiments under the typical range of $h$ in air. Also, we conducted a macroscopic simulation to calculate thermal deformation due to the temperature variation (figure 6(d)). Here, a fixed boundary condition is used because the bottom surfaces are fixed to the sample holder. After laser irradiation for 60 s, the total thermal displacement distribution in the structure becomes a Gaussian shape according to the temperature distribution. The maximum displacement is about 55.7 nm even at the center of the Gaussian beam region. The thermal displacement is around 0.05 (where $\lambda$ is 1064 nm), and the wavefront distortion due to this amount of deformation is negligibly small. Furthermore, based upon this thermal analysis simulation, we can give feedback on the grating design process such as material selection and grating pattern shape. Also we can acquire critical information about device operations such as the relationship between diffraction efficiency and temperature rise, and information about where thermal deformation is most likely to occur.

3. Conclusion

We have combined experimental and numerical methods to realize an MLDG that has high heat tolerance. RCWA, FDTD and FEM simulation methods were used to design the MLDG structures and to examine their electric field characteristics. We used single-beam LIL to fabricate the MLDG on a 20 mm thick fused silica substrate, which could suppress thermal deformation and corresponding wavefront distortion. The fabricated MLDG was characterized using a high-power CW fiber laser and its thermal characteristics were observed using a thermal camera. The proposed thermal analysis method confirmed that it can predict the actual experimental results. The developed experiment/simulation methods and device can be widely applied to high-power laser beam applications such as chirped-pulse combination and spectral beam combining.

Acknowledgments

This work was supported by Agency for Defense Development of Korea. Among the authors, IK and SS acknowledge the Global Ph.D. Fellowships from National Research Foundation of Korea (NRF-2016H1A2A1096519 and NRF-2017H1A2A1043322), respectively. The authors thank Professor Gun-Young Jung at Gwangju Institute of Science and Technology (GIST), Korea for the technical support of diffraction grating fabrication.

Author contributions

JR, KL and IK conceived the idea and designed the project. IK and TL fabricated devices. SS, JM, KHL and JHL did related numerical simulations. KL, IK and TL did optical and thermal characterizations. IK, SS, JM, KHL and JR prepared the manuscript. JR guided the research. All authors discussed the results and confirmed the final manuscript.

Conflict of interest

The authors declare no competing interests.

ORCID iD

Junsuk Rho  https://orcid.org/0000-0002-2179-2890

References

[1] Strickland D and Mourou G 1985 Compression of amplified chirped optical pulses Opt. Commun. 56 219–21
[2] Backus S, Durfee C G, Murnane M M and Kapteyn H C 1998 High power ultrafast lasers Rev. Sci. Instrum. 69 1207–23
[3] Daneu V et al 2000 Spectral beam combining of a broad–stripe diode laser array in an external cavity Opt. Lett. 25 405–7
[4] Bockove E J 2002 Theory of spectral beam combining of fiber lasers IEEE J. Quantum Electron. 38 432–45
[5] Loftus T H et al 2007 Spectrally beam-combined fiber lasers for high-average-power applications IEEE J. Quantum Electron. 13 487–97
[6] Wirth C et al 2010 2kW incoherent beam combining of four narrow linewidth photonics crystal fiber amplifiers Opt. Express 17 1178–83
[7] Boyd R D et al 1995 High-efficiency metallic diffraction gratings for laser applications Appl. Opt. 10 1697–706
[8] Palmie S, Neauport J, Baclet N, Lavaste E and Dupuy G 2009 High reflection mirrors for pulse compression gratings Opt. Express 17 20430–9
[9] Neauport J, Bonod N, Hocquet S, Palmier S and Dupuy G 2010 Mixed metal dielectric gratings for pulse compression Opt. Express 18 23776–83
[10] Wen-Fei Z, Wei-Jin K, Mao-Jin Y, Jun-Hai L and Xin S 2012 Broadband and high efficiency metal multi-layer dielectric gratings based on non-quarter-wave coatings as a reflective mirror Chin. Phys. B 21 094218
[11] Perry M D et al 1995 High efficiency multilayer dielectric diffraction gratings Opt. Lett. 20 940–2
[12] Stuart B C, Feit M D, Rubenchik A M, Shore B W and Perry M D 1995 Laser-induced damage in dielectrics with nanosecond to subpicosecond pulses Phys. Rev. Lett. 74 2248–51
[13] Wei H and Li L 2003 All-dielectric reflection gratings: a study of the physical mechanism for achieving high efficiency Appl. Opt. 42 6255–60
[14] Liu S et al 2006 Optimization of near-field optical field of multi-layer dielectric gratings for pulse compressor Opt. Commun. 267 59–57
[15] Neauport J et al 2007 Effect of electric field on laser induced damage threshold of multilayer dielectric gratings Opt. Express 15 12508–22
[16] Liu S et al 2007 Optimization of thin-film design for multi-layer dielectric grating Appl. Surf. Sci. 253 3642–8
[17] Kong F et al 2012 Effect of pulse duration on laser induced damage threshold of multilayer dielectric gratings Proc. SPIE 8530 85300L
[18] Qiao J et al 2010 In situ detection and analysis of laser-induced damage on a 1.5-m multilayer-dielectric grating compressor for high-energy, petawatt-class laser systems Opt. Express 18 10423–31
[19] Nguyen D N et al 2011 Femtosecond pulse damage thresholds of dielectric coatings in vacuum Opt. Express 19 5690–7
[20] Poole P, Trendafilov S, Shvets G, Smith D and Chowdhury E 2013 Femtosecond laser damage threshold of pulse compression gratings for petawatt scale laser systems Opt. Express 21 1–26351
[21] Alessi D A et al 2015 Picosecond laser damage performance assessment of multilayer dielectric gratings in vacuum Opt. Express 23 15532–44
[22] Jena S, Tokas R, Kamble N M, Thakur S and Sahoo N K 2014 Optical properties and laser damage threshold of HfO2–SiO2 mixed composite thin films Appl. Opt. 53 850–60
[23] Howard H P et al 2013 Improving the temperature of high-laser-damage-threshold, multilayer dielectric pulse-compression gratings through low-temperature chemical cleaning Appl. Opt. 52 1682–92
[24] Cui Y, Zhao Y, Yu H, He H and Shao J 2008 Impact of organic contamination on laser induced damage threshold of high reflectance coatings in vacuum Appl. Surf. Sci. 254 5990–3
[25] Murakami H et al 2012 Influences of oil-contamination on LIDT and optical properties in dielectric coatings Proc. SPIE 8530 853024
[26] Favrat O, Sozet M, Toven-Pécault I, Lamaninére L and Neauport J 2014 Influence of organic contamination on laser induced damage of multilayer dielectric mirrors by subpicosecond laser pulses Proc. SPIE 9237 923707
[27] Yang L, Wu Z and Zhang B 2016 Influence of thermal deformation of a multilayer dielectric grating on a spectrally combined beam Appl. Opt. 55 9091–100
[28] Li L et al 2017 Beam modulation due to thermal deformation of grating in a spectral beam combining system Appl. Opt. 56 5511–19
[29] Xu J et al 2018 Study of the key factors affecting temperature of spectral-beam-combining system Opt. Express 26 21675–84
[30] Xu J et al 2018 Dependence of temperature and far-field beam quality on substrate thickness of a spectral beam combining grating with 13.4 kW/cm² laser irradiation Appl. Opt. 57 D165–70
[31] Moharam M G, Grann E B, Pommet D A and Gaylord T K 1995 Formulation for stable and efficient implementation of the rigorous coupled-wave analysis of binary gratings J. Opt. Soc. Am. A 12 1068–76
[32] Lalanne P and Morris G M 1996 Highly improved convergence of the coupled-wave method for TM polarization J. Opt. Soc. Am. A 13 779–84