Three-layer high-efficiency wideband metal-mirror-based grating

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A novel wideband three-layer high-efficiency metal-mirror-based grating is designed and investigated. It consists of an Ag slab and a three-layer rectangular-groove dielectric-grating structure. Both TE and TM polarizations exhibit high efficiency in -1st order with good angular bandwidth and spectral bandwidth. Compared with the reported high-efficiency grating, the efficiency can be improved. Moreover, a wide spectral width of 150 nm and a broad angular width of 5.6° can be shown. The modal method and rigorous coupled-wave analysis are used together to study grating parameters in this optimization.

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1. Introduction

Periodic structures [1-5] are very important optical devices that can be used as splitters [6-8], spectrometers [9], photodetectors [10], sensors [11-16], laser systems [17-20], quarter-wave plates [21], fiber systems [22-25], couplers [26-29]. For double-groove grating [30], almost 100% reflectivity is obtained in -1st order reflection for a resonant wavelength of 1550 nm and an incident angle of 60°. Moreover, diffraction efficiency over 99.7% is achieved in -1st diffraction order of TE polarization at 1030 nm [31]. With further research multilayer gratings, the two-layer grating [32] and three-layer grating [33,34] are reported. A three-layer diffraction grating can show high efficiency only in -1st diffraction order with the broad spectral and angular bandwidths based on Littrow incident condition [35]. A pyramidal metal-dielectric multilayer rectangle grating structure is investigated [36]. The absorbance is higher than 90% in a wavelength range of 2321-4631 nm at normal incidence and the broadband absorption performance remains excellent over a wide incident angle range, which is beneficial for real application. Based on the vector grating theory, diffraction properties can be not only numerically calculated using rigorous coupled-wave analysis (RCWA) method [37] but also well explained by modal method [38]. A high-efficiency polarization-independent wideband multilayer dielectric reflective grating [39] has been reported with bullet-alike cross-section fused-silica structure for high-power laser incoherent spectral beam combining. A three-layer trapezoidal-groove reflective grating with broad bandwidth and large fabrication tolerances [33] is designed by using RCWA method, where efficiencies of experimental measurements are consistent with theoretical calculations based on numerical optimization.

In this paper, the three-layer metal-mirror-based grating device is designed to obtain high-efficiency in -1st order for transverse electric (TE) polarization and transverse magnetic (TM) polarization. The photoresist mask method and ion beam etching method can be used to fabricate such a reflective grating.

2. Physical design and numerical calculation

Fig. 1 shows the schematic of three-layer metal-mirror-based grating, where the rectangular grating ridges are made up of two kinds of dielectric materials with three different etching depth. The two materials are fused silica with the refractive index of $n_3 = n_1 = 1.45$ and Ta_2O_5 with the refractive index of n_2 = 2.0, and each thickness of three gating layers is h_1, h_2 and h_3, respectively. The grating is etched in fused silica. As a reflection element, the incident wave will propagate through the grating region and be reflected by the Ag slab with refractive index of n_0 and thickness of h_m to obtain high efficiency in the -1st order. In addition, d is the period of the novel grating and the duty cycle is defined by ratio of ridge width to period. A plane polarized light with a working wavelength λ of 1550 nm incidents from the air with the refractive index of n_4 = 1.0 on the three-layer grating at the incident Bragg angle of $\theta = \sin^{-1}(\lambda/(2n_4d))$.

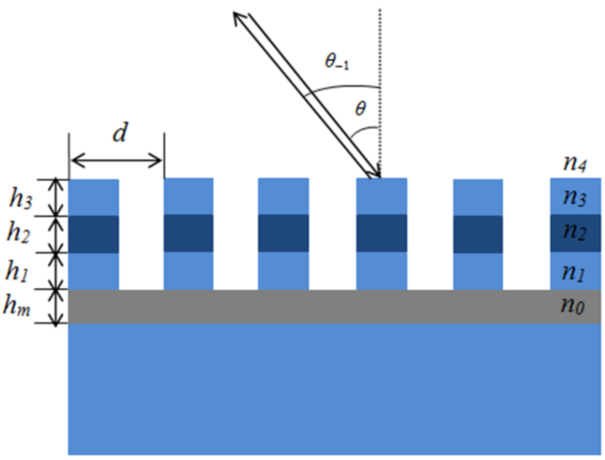


Fig. 1. Schematic of three-layer rectangular-groove metal-mirror-based grating under Bragg angle incidence (color online)

The coupled mechanism in the three-layer metal-mirror-based grating can be well explained by the modal method. When the incident wave propagates in the grating, two modes are excited, and each grating mode has almost the same energy from the incident wave. Due to the asymmetry between the two modes, the effective refractive indices n_{eff} of mode 0 and mode 1 are different. The effective index difference between the mode 0 and mode 1 can contribute to the coupling efficiency in the -1st order. Therefore, the calculated effective indices from the proper function [38] can be described as:

$$F(n_{eff}^2) = \cos(\frac{2\pi d \sin\theta}{\lambda}) \cdot \quad (1)$$

Due to the duty cycle of f=0.7 and period of d=1270 nm are given by rigorous calculation, the effective indices in each layer can be calculated with the different refractive index of grating ridge. For TE and TM polarizations, effective indices in the three layers are shown in Table 1.

Table 1. Effective indices in three grating layers with duty cycle of f=0.7 and period of d=1270 nm at an incident wavelength of 1550 nm

Mode	0	1
TE: Layer 1, n_{eff}	1.2997	1.0917
TE: Layer 2, n_{eff}	1.8808	1.5812
TE: Layer 3, n_{eff}	1.2997	1.0917
TM: Layer 1, n_{eff}	1.2478	1.0630
TM: Layer 2, n_{eff}	1.8281	1.3841
TM: Layer 3, n_{eff}	1.2478	1.0630

The phase difference can be accumulated at the interface between the transmission grating and the Ag slab, which determines the reflection efficiency of -1st and 0th. After being reflected by the Ag slab, the two diffraction waves will be diffracted by the grating again to form four possible modes. The interference in the four modes will determine the final diffraction efficiency of the reflective gating. In theory, the accumulated phase difference in three layers should satisfy the odd-numbered multiples of π, efficiency of -1st diffractive order can attain nearly 100% result. Thus, the related expression is obtained:

$$\eta_{-1st} = \sin^2\left(\frac{\Delta\varphi}{2}\right), \quad (2)$$

where the $\Delta\varphi$ is the phase difference. This equation should be satisfied both TE polarization and TM polarization. Hence, the relative expressions for two polarizations in three layers are

$$\Delta\varphi^{TE} = \frac{4\pi}{\lambda}\left[\left(n_{0eff}^{1TE} - n_{1eff}^{1TE}\right)h_1 + \left(n_{0eff}^{2TE} - n_{1eff}^{2TE}\right)h_2 + \left(n_{0eff}^{3TE} - n_{1eff}^{3TE}\right)h_3\right] = (2m+1)\pi \qquad (3)$$

and

$$\Delta\varphi^{TM} = \frac{4\pi}{\lambda}\left[\left(n_{0eff}^{1TM} - n_{1eff}^{1TM}\right)h_1 + \left(n_{0eff}^{2TM} - n_{1eff}^{2TM}\right)h_2 + \left(n_{0eff}^{3TM} - n_{1eff}^{3TM}\right)h_3\right] = (2n+1)\pi \qquad (4)$$

with m and n are arbitrary integers, and n_{keff}^{iTx} is the effective indices of different Tx polarization of the mode k in layer i. The equations (2) to (4) express the interference effect between the coupled modes. The three equations are derived from the modal method of the waveguide. Figure 2 shows four different lines that TE and TM polarizations have high efficiency based on above three equations for a duty cycle of 0.7 under an operating wavelength 1550 nm. In Fig. 2, the thickness of h_m is 0.1 μm for metal. There are two intersections in these four lines with duty cycle of 0.7 and period of 1270 nm. In order to fabricate technology easier, one intersection between red line and green line need to be considered, where an optimized polarization-independence device is obtained with h_1 = 0.91λ=1.41 μm and h_2 = 0.24λ = 0.37 μm. It implies that the grating parameters can be optimized near this point to obtain a high-efficiency reflection grating with the duty cycle of 0.7 and period of 1270 nm.

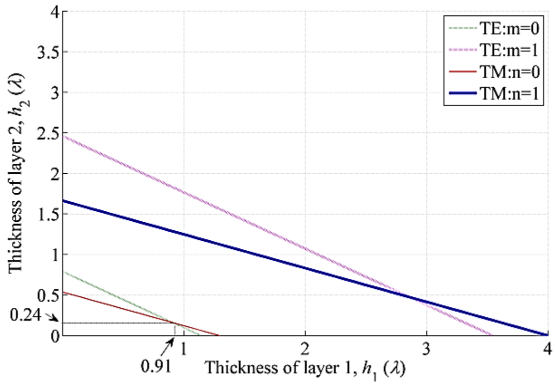
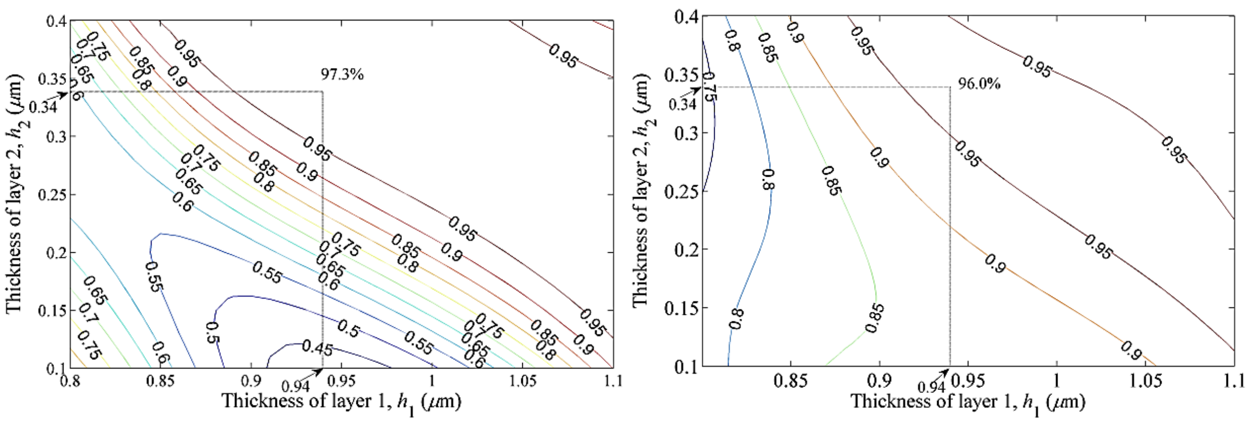


Fig. 2. The four different lines of high efficiency for both TE polarization and TM polarization on account of Eqs. (3,4) for a duty cycle of 0.7 under an operating wavelength of 1550 nm (color online)

Through modal methods, we can interpret the physical diffraction process of the grating and obtain an approximation of the grating parameters. In order to obtain accurate grating parameters, rigorous calculation is used. With the fixed h_3 = 0.1 μm. Fig. 3 shows the contour of efficiency of -1st for TE polarization and TM polarization. As can be seen from Fig. 3, three-layer metal-mirror-based grating can diffract the TE polarization and TM polarization in the -1st with the high efficiency of 97.3% and 96.0%, respectively. The optimized thicknesses of h_1 and h_2 is 0.94 μm and 0.34 μm respectively.



(a) *(b)*

Fig. 3. Contour of the -1st reflection efficiency for (a) TE polarization and (b) TM polarization (color online)

3. Bandwidth optimization

There are many gratings reported about high-efficiency in -1st order, including single-layer [31] or two-layer reflection grating [32]. Fig. 4 shows the reflection efficiency as a function of wavelength. From Fig. 4, one can see that the diffraction efficiency is higher than 95% in the range from 1447 nm to 1597 nm for both TE and TM polarizations.

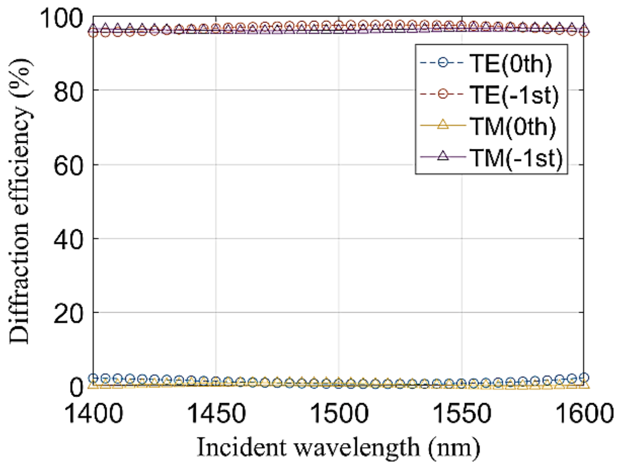
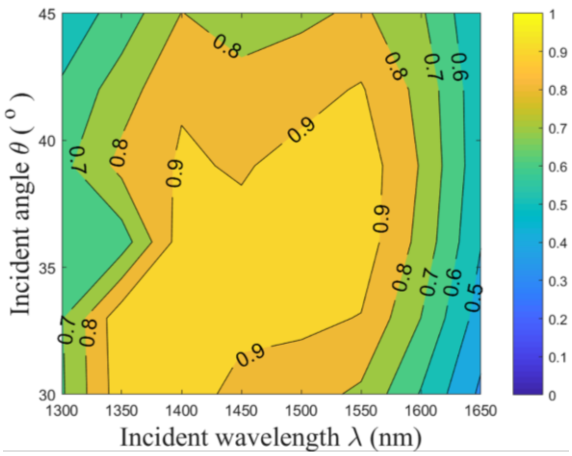
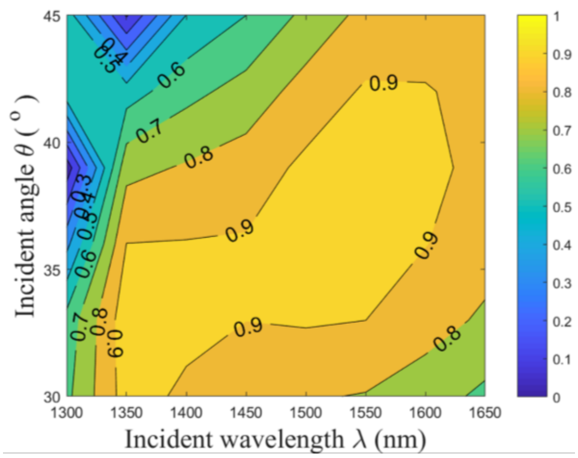


Fig. 4. The reflection efficiency versus incident wavelength for both TE polarization and TM polarization (color online)

Fig. 5 shows reflection efficiency versus incident wavelength and incident angle at a duty cycle of 0.7 with optimized grating thickness for TE and TM polarizations. It can be seen from Fig. 5 that the reflection efficiency of the -1st orders is affected by different wavelengths and angles. The diffraction efficiency of the -1st order can show more than 80% within the coverage of incident wavelengths from 1416 nm to 1612 nm and the incident angle from 33.3° to 43.4°. Considering only the angle variation, the efficiencies are more than 95% in the -1st order in bandwidth range of 35.0°-40.6° for TE and TM polarizations.



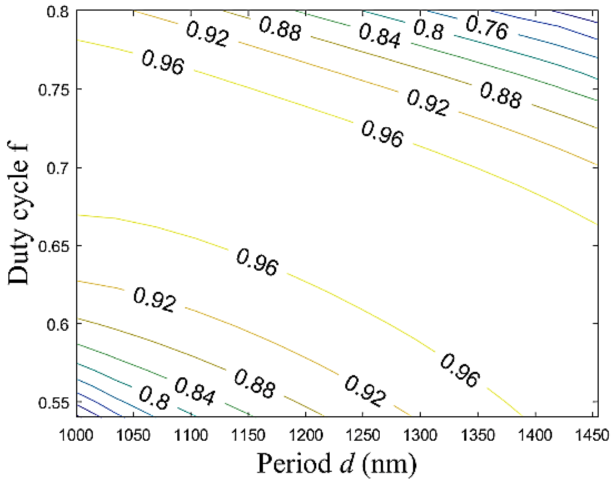
(a)



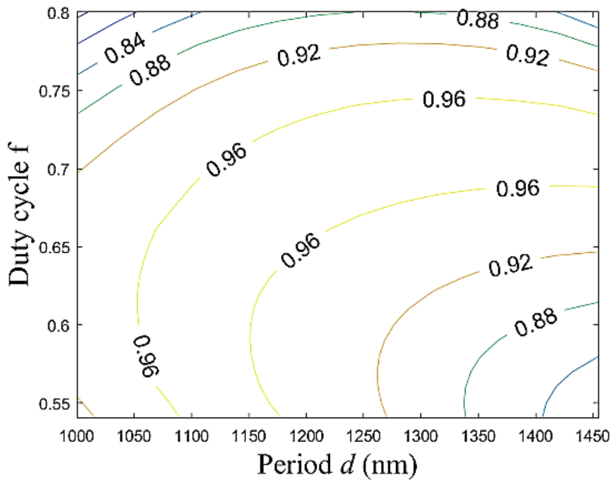
(b)

Fig. 5. Contour of the reflection efficiency of the -1st order versus incident wavelength and incident angle for (a) TE polarization and (b) TM polarization (color online)

The validity and fabrication process can be indirectly verified by some reported grating-based works [40,41]. The metal layer and three dielectric layers are coated on the substrate. Through lithography and dry etching, the designed elements can be demonstrated in experiments. Therefore, the three-layer high-efficiency metal-mirror-based grating presented in this paper can be potentially verified by using the similar techniques. In practical applications, the manufacturing tolerance of the designed grating needs to be considered. Fig. 6 shows the effect of grating period and duty cycle on reflection efficiency. It can be seen from Fig. 6 that when the grating period is in the range of 1120 nm to 1330 nm and the duty cycle is from 0.67 to 0.72, reflection efficiencies of -1st order exceed 95% for TE and TM polarizations.



(a)



(b)

Fig. 6. Contour of the reflection efficiency of the -1st order versus grating period and duty cycle for (a) TE polarization and (b) TM polarization (color online)

4. Conclusion

A polarization-independent wideband three-layer reflective grating is analyzed and calculated by modal method and RCWA. The modal method is used to evaluate the three thicknesses of three layers and we obtain the three thicknesses of 1.41 μm, 0.24 μm and 0.1 μm, respectively. Simplified modal analysis shows that phase difference accumulated by the two modes will determine the reflection efficiency of -1st order. When the phase difference is odd multiples of π for both TE and TM polarizations, polarization-independent high-efficiency diffraction can be obtained. With the accurate grating parameters calculated by RCWA, the efficiency of -1st can achieve 97.3% and 96.0% for TE polarization and TM polarization, respectively. The optimized reflective grating exhibits diffraction efficiency more than 95% within 150 nm incident wavelength bandwidth for both TE and TM polarizations. At the same time, the incident angular bandwidth of 5.6° is enhanced. Therefore, the designed three-layer metal-mirror-based grating-based device should be very useful with wideband property for incident wavelength and angle in numerous optical systems.

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References

[1] J. Li, Z. Zhang, K. Fu, Optik **199**, 163397 (2019).

[2] A. Biswas, A. Sonmezoglu, M. Ekici, A. S. Alshomrani, M. R. Belic, Optik **195**, 163146 (2019).

[3] W. Zhu, B. Wang, C. Gao, K. Wen, Z. Meng, Z. Nie, Q. Wang, X. Xing, L. Chen, L. Lei, J. Zhou, Mod. Phys. Lett. B **33**(25), 1950305 (2019).

[4] Y. Chen, L. Chen, X. Wang, W. Liu, Optik **168**, 598 018).

[5] A. Biswas, A. Sonmezoglu, M. Ekici, A. S. Alshomrani, M. R. Belic, Optik **194**, 163020 (2019).

[6] C. Gao, B. Wang, K. Wen, Z. Meng, Z. Nie, X. Xing, L. Chen, L. Lei, J. Zhou, Opt. Commun. **452**, 395 (2019).

[7] M. A. Butt, S. N. Khonina, N. L. Kazanskiy, Laser Phys. **28**(11), 116202 (2018).

[8] C. Gao, B. Wang, C. Fu, J. Fang, K. Wen, Z. Meng, Z. Nie, L. Chen, L. Lei, J. Zhou, J. Optoelectron. Adv. M. **21**(7-8), 429 (2019).

[9] B. Du, J. Zhu, Y. Mao, K. Wang, H. Chen, X. Hou, Opt. Commun. **410**, 338 (2018).

[10] M. Billet, E. Peytavit, Optik **154**, 828 (2018).

[11] W. Jin, Y. Xu, Y. Jiang, Y. Wu, S. Yao, S. Xiao,

Y. Qi, W. Ren, S. Jian, Laser Phys. **28**(2), 025103 (2018).

[12] J. Xu, Z. Dziong, A. Cabani, Laser Phys. **28**(12), 125101 (2018).

[13] P. Cheng, L. Wang, Y. Pan, H. Yan, D. Gao, J. Wang, H. Zhang, Laser Phys. **29**(2), 025107 (2019).

[14] A. Dhibi, Phys. Scr. **94**(10), 105602 (2019).

[15] R. T. Yang, M. Dong, F. Meng, Y. Song, L. Zhu, Laser Phys. **28**(10), 105001 (2018).

[16] D. Srivastava, U. Tiwari, B. Das, Opt. Commun. **410**, 88 (2018).

[17] M. Wang, Z. Li, L. Liu, Z. Wang, X. Xu, Laser Phys. **28**(12), 125102 (2018).

[18] C. Sun, M. Wang, Y. Dong, S. Ye, S. Jian, Laser Phys. **28**(10), 105102 (2018).

[19] J.-R. He, S. Xu, L. Xue, Phys. Scr. **94**(10), 105216 (2019).

[20] M. H. Pham, M. Cadatal-Raduban, D. V. Pham, T. X. Nguyen, M. V. Luong, K. Yamanoi, T. Shimizu, N. Sarukura, H. D. Nguyen, Laser Phys. **28**(8), 085802 (2018).

[21] A. Hu, F. Chu, C. Guo, G. Li, J. Wu, Optik **163**, 120 018).

[22] W. Lei, H. Chen, Optik **172**, 526 (2018).

[23] R.-Q. Lv, Q. Wang, H.-F. Hu, J. Li, Optik **158**, 71 (2018).

[24] M. Xie, H. Gong, J. Zhang, C.-L. Zhao, X. Dong, Opt. Eng. **57**(11), 117107 (2018).

[25] D. Hou, J. Kang, X. Wang, Q. Zhang, X. Zhou, C. Zhao, X. Dong, Opt. Eng. **57**(4), 046101 (2018).

[26] J. Wang, C. Liu, G. Wang, Y. Sun, Optik **182**, 114319).

[27] S. Nambiar, S. K. Selvaraja, Opt. Eng. **57**(1), 017115 (2018).

[28] Y. Dai, H. Xu, H. Wang, Y. Lu, P. Wang, Opt. Commun. **416**, 66 (2018).

[29] T. Sharma, H. Kwon, J. Park, S. Han, G. Son, Y. Jung, K. Yu, Opt. Commun. **427**, 452 (2018).

[30] K. Ito, H. lizuka, AIP Adv. **3**(6), 062119 (2013).

[31] B. Dannecker, M. Rumpel, T. Graf, M. A. Ahmed, Opt. Lett. **43**(16), 4017 (2018).

[32] B. Wang, W. Shu, L. Chen, L. Lei, J. Zhou, IEEE Photon. Technol. Lett. **26**(5), 501 (2014).

[33] H. Guan, H. Chen, J. Wu, Y. Jin, F. Kong, S. Liu, K. Yi, J. Shao, Opt. Lett. **39**(1), 170 (2014).

[34] R. H. Fan, D. Liu, R. W. Peng, W. B. Shi, H. Jing, X. R. Huang, M. Wang, Opt. Exp. **26**(1), 516 (2018).

[35] H. Li, B. Wang, IEEE Photon. J. **9**(1), 6500407 (2017).

[36] J. Wu, Opt. Mater. **62**, 47 (2016).

[37] M. G. Moharam, D. A. Pommet, E. B. Grann, T. K. Gaylord, J. Opt. Soc. Am. A **12**(5), 1068 (1995).

[38] I. C. Botten, M. S. Craig, R. C. Mcphedran, J. L. Adams, J. R. Andrewartha, Opt. Acta. **28**(3), 413 (1981).

[39] H. Cao, J. Wu, J. Yu, J. Ma, Appl. Opt. **57**(4), 900 (2018).

[40] J. Feng, C. Zhou, B. Wang, J. Zheng, W. Jia, H. Cao, P. Lv, Appl. Opt. **47**(35), 6638 (2008).

[41] T. Wu, C. Zhou, J. Zheng, J. Feng, H. Cao, L. Zhu, W. Jia, Appl. Opt. **49**(24), 4506 (2010).

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