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Cost-effective double-layer antireflection coatings in mid-wavelength infrared band

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HIGHLIGHTS

- Cost-effective narrow-band double-layer AR coatings for laser applications in mid-infrared band.
- Simple and visualized design method of vector graphics.
- High performance of the coating preparation which is near the theoretical limit.

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ABSTRACT

In this letter, design and preparation of cost-effective double-layer antireflection (AR) coatings in mid-wavelength infrared band is investigated. The method of vector graphics which is simple and visualized for coatings designs with only a few layers is applied to design narrow-band double-layer AR coatings with high performance and low cost for laser applications. The experiment result verifies the design very well with peak transmittance very close to the theoretical limit.

1. Introduction

Demand for antireflection coatings in mid-wavelength infrared domain has increased rapidly, for laser sources such as optical parametric oscillator (OPO) or quantum cascade laser (QCL) in mid-wavelength infrared domain have been applied to many fields, such as gas detection, infrared measurement [1–4]. Antireflection coatings in visible and near-infrared domain are usually designed as stacks with many layers which possess wide antireflective band [5,6]. However, this type of design will lead to large thickness of coatings in mid-wavelength infrared domain which can lead to long-time deposition, mechanical stress, uniformity trouble, high intensity of intra-cavity fields, increase of absorption and scattering, etc. [7,8]. Single-layer antireflection coating is still with too large single-layer thickness [9]. Contrastively, double-layer antireflection coatings designed for particular wavelength or narrow antireflective band can be prepared with higher performance, moderate thickness and lower cost.

In this paper, design and preparation of narrow-band double-layer AR coatings for mid-infrared band using method of vector graphics is investigated. This design will meet the needs for high-performance and low-cost coatings in laser applications.

2. Material choice

In mid-wavelength infrared domain, several materials could be chosen as substrate, such as sapphire, CaF_2, ZnSe, silicon and germanium. In this paper, GaAs is chosen to be the substrate material in our designs and experiments. The incident medium is air ($n \approx 1.0$). The substrate is of GaAs ($n \approx 3.32$, absorption is very low at wavelength of 4.6 μm). The system of coating materials is combination of SiO_2 ($n \approx 1.39$, absorption is reasonable in thin film at wavelength of 4.6 μm) and TiO_2 ($n \approx 2.3$, absorption is reasonable in thin film at wavelength of 4.6 μm). Since the coating system of SiO_2/TiO_2 is durable and has mature preparation process which is widely used in such as lasers applications and solar cells, AR coatings with high performance and low cost could be expected.

3. Design

Usually, method of adjusting the thicknesses of each layer with given refraction index in order to reduce the reflection at design wavelength is practical. The exact thicknesses of coatings could be obtained by solving relative equations. Contrastively, vector

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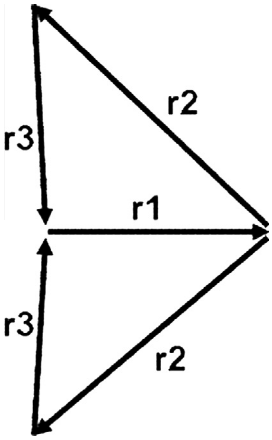

Fig. 1. The graphic of two mirror triangles formed by interface vectors from coating system of SiO_2-TiO_2-substrate.

graphics is a simple and visual method to obtain thicknesses of each layer within reasonable error.

Suppose n_0, n_1, n_2 and n_3 are the refraction index of air, 1st layer, 2nd layer and GaAs, respectively while the corresponding interface amplitude reflection coefficient r_p ($p = 1, 2, 3$) can be expressed by formula (1).

In order to reduce the reflectivity at design wavelength to zero, vectors of r_1, r_2 and r_3 should form a closed triangle as show in Fig. 1. Each vector triangle has its mirror counterpart which produces a pair of effective solutions. Here, the sequence of 1st layer and 2nd layer is SiO_2 and TiO_2. Then the vector triangles can be transferred to polar coordinates and the rotation angles b12 and b23 can be solved, as shown in Fig. 2 and Table 1. The phase thicknesses of the two layers are half of b12 and b23, respectively. When normal incidence is considered only, the physical thicknesses of the two layers could be acquired by formula (2). The two groups of effective solutions are shown in Table 2.

When the sequence of 1st layer and 2nd layer is changed as TiO_2 and SiO_2, another pair of mirror vector triangles can be obtained, as shown in Fig. 3. The vector graphics are transferred to polar coordination which is shown in Fig. 4 and the phase thicknesses are shown in Table 3. Finally, the other two groups of effective solutions could be obtained, as shown in Table 4.

All the four groups of effective solutions shown in Tables 2 and 4 can reduce the reflection at the design wavelength to zero, ignoring other influence factors. However, when absorption, scattering and preparation cost of coatings are considered, the optimal solution should be the solution (a) in Table 4, obviously.

Table 1
Computing results of two groups of phase thicknesses from Fig. 2.

	Value		Value (a)	Value (b)
$r1$	−0.1632	b12	0.7368π	1.2632π
$r2$	−0.2466	b23	0.7699π	1.2301π
$r3$	−0.1815			

Table 2
Two groups of effective solutions from Table 1.

	Material	Index	Solution (a)	Solution (b)
	Air	1.0		
1	SiO_2	1.39	610 nm	1045 nm
2	TiO_2	2.3	385 nm	615 nm
	GaAs	3.32		

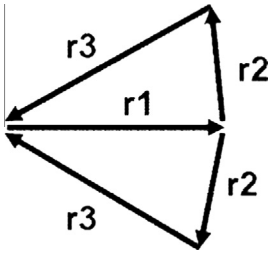

Fig. 3. The graphic of two mirror triangles formed by interface vectors from coating system of TiO_2-SiO_2-substrate.

4. Experiments and results

In order to verify the coating design above, preparation of single side coating on GaAs substrate using method of e-beam evaporation has been set up. The chamber base pressure is about 1e-06 Pa. The substrate temperature is 200 °C. The grow thickness of SiO_2 and TiO_2 is set at 316 nm and 210 nm, respectively. After preparation, an FTIR spectrometer is used to measure the transmission spectrum of the AR coating. Fig. 5(a) shows the theoretical transmission spectrum. The peak transmittance in theory is 71% because of single side AR coating and high Fresnel reflection of the other side which is caused by the high-refraction-index substrate. Fig. 5(b) shows the original experimental transmittance

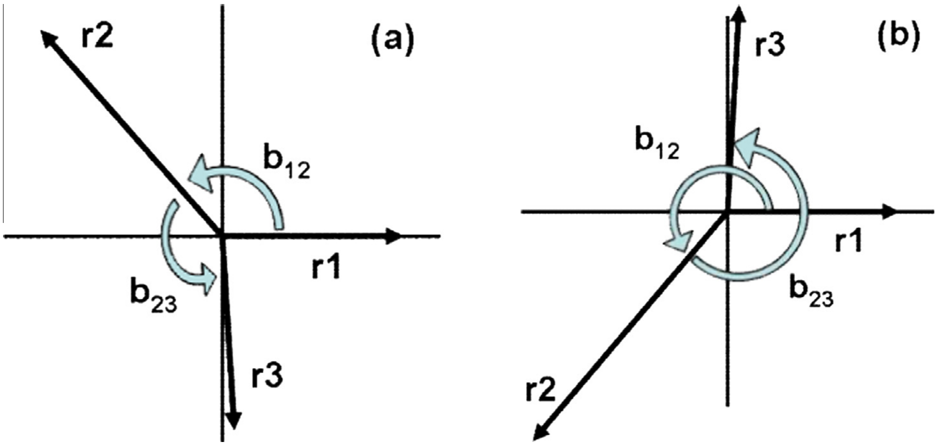

Fig. 2. The two groups of vectors graphics by transferring the two mirror triangles from Fig. 1 to polar coordinates.

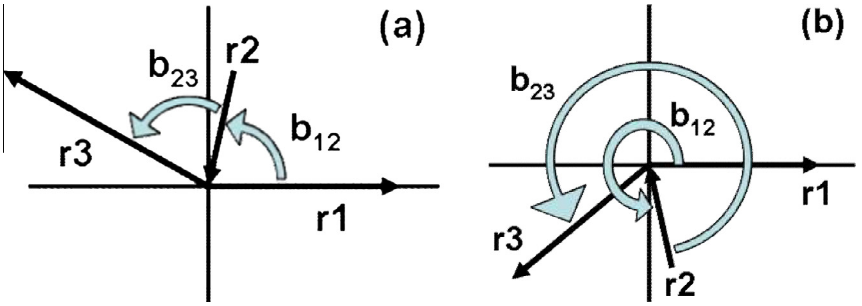

Fig. 4. The two groups of vectors graphics by transferring the two mirror triangles from Fig. 3 to polar coordinates.

Table 3
Computing results of two groups of phase thicknesses from Fig. 4.

	Value		Value (a)	Value (b)
*r*1	−0.3939	b12	0.4204π	1.5796π
*r*2	0.2466	b23	0.3815π	1.6185π
*r*3	−0.4098			

Table 4
Two groups of effective solutions from Table 3.

	Material	Index	Solution (a)	Solution (b)
	Air	1.0		
1	TiO_2	2.3	210 nm	790 nm
2	SiO_2	1.39	316 nm	1339 nm
	GaAs	3.32		

spectrum and serious Fabry–Perot fringes can be observed obviously due to the only 300 μm thickness of substrate which allows multiple antireflections between the double sides. In order to extract effective transmittance data from the original ones, a fitting curve is created and shown in Fig. 5(c). The experimental peak transmittance of 70% is obtained which is very close to the theoretical limit except for a little blue shift of peak transmittance wavelength due to the slightly insufficient growth time of TiO_2 layer in the experiment.

5. Conclusion

In this letter, design and preparation of cost-effective double-layer antireflection coatings in mid-infrared is investigated. The design method of vector graphics is applied for double-layer AR coatings design. The optimal solution can be chosen out from all the effective solutions. The experimental result verifies the coating design very well with peak transmittance of 70% which is very

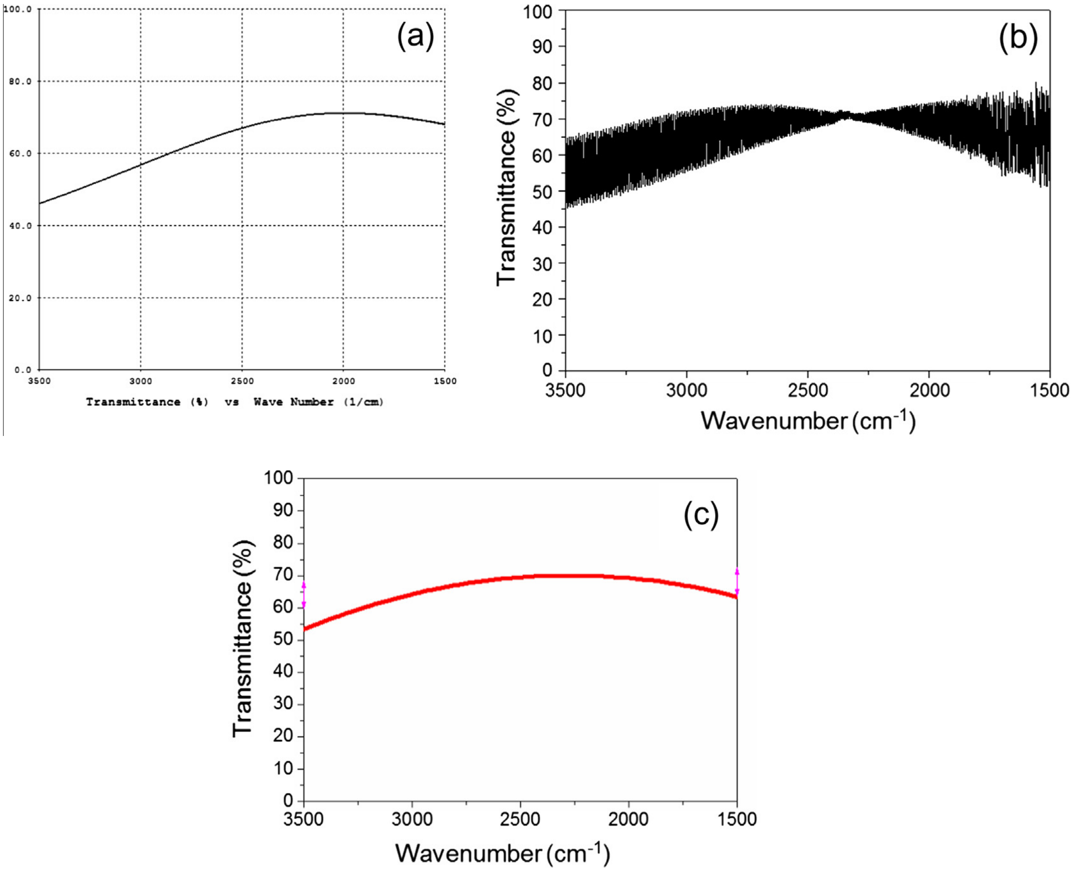

Fig. 5. The theoretical (a) and original experimental (b) transmittance spectrum of the optimal coating system. (c) shows the fitting curve of the transmittance spectrum.

close to the theoretical limit. Since the designed double-layer AR coating utilizes ordinary materials with moderate thickness, it can be mass produced with high performance and low cost so as to meet the needs for laser applications in mid-infrared band.

Conflict of interest

There is no conflict of interest.

Acknowledgements

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Appendix A

$$r_p = \frac{n_{p-1} - n_p}{n_{p-1} + n_p} \qquad (p = 1, 2, 3) \tag{1}$$

$$d_p = \frac{\lambda}{4 n_p \pi} b_{p(p+1)} \qquad (p = 1, 2) \tag{2}$$

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