# Harmonic beam splitter design and fabrication

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Two problems of half-wave hole and high ripples in the transmittance region for a harmonic beam splitter had been pointed out and analyzed. Based on the application of a half-wavelength control and a new admittance matching methods, a harmonic beam splitter was designed and fabricated. The former method eliminated the half-wave hole fundamentally, and the latter smoothed high ripples in the transmittance region effectively. The matching stack consisted of a symmetrically periodic structure and provided a complete matching at the desired wavelength, i.e., both conditions for the equivalent admittance and phase thickness were fulfilled. Furthermore, both the theoretical and the tested curves had been given, and a good agreement between them was obtained.

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Harmonic beam splitter is one of vital optical components in diode pumped Nd:$YVO_4$ frequency doubling lasers, which provides high reflectance at the fundamental wavelength and high transmittance at the doubled one and *vice versa.* However, there are some problems in the process of preparation, such as a reflective peak at the half of center wavelength, which is called half-wave hole, and high ripples in the transmittance region. These problems affect the harmonic beam splitter's optical property seriously. Research[1] had shifted half-wave hole from the desired wavelength to other region by selecting the control wavelength, but this method had not eliminated the half-wave hole ultimately. High ripples had been still in the passband, as a result such a low transmittance as 92.60% at 0.532 $\mu$m had been given[2]. Studies[3,4] indicated that the half-wave hole was due to the dispersion and refractive index inhomogeneity of film materials and error accumulation of layers thickness, and high ripples in the transmittance region attributed to the equivalent admittance mismatching between the film stack and its adjacent media[5]. To resolve these difficulties fundamentally, a new admittance-matching method and half-wavelength control were employed in our design in this paper, and the harmonic beam splitter was fabricated by radio frequency ion beam sputtering (RF IBS) to enhance its optical characteristics effectively.

The harmonic beam splitter presented here was designed to have high reflectance ($R \geq 99.95\%$) at $\lambda_0 = 1.064$ $\mu$m and good transmittance ($T \geq 99.0\%$) at the Nd:YAG doubled wavelength ($\lambda_m = 0.532$ $\mu$m) and was deposited on a BK7 glass substrate with the refractive index $n_s = 1.52$. In order to relax the instability of preparing process factors and the reliability of working conditions, a wide passband at about 0.532 $\mu$m was necessary. Moreover, a high splitting ratio ($S \geq 10^3$) of the beam splitter was required. The basic stack was a high reflectance one with its center wavelength at 1.064 $\mu$m, which was realized with such a structure of the type: $(HL)^{13}$H0.5L, using $Ta_2O_5$ as high index material and $SiO_2$ as low index material.

In the case of maintaining deposition rate constantly and other process parameters stably, refractive index inhomogeneity of film materials and error accumulation of layers thickness could be neglected[6]. Thus the dispersions of film materials were the main cause of half-wave hole. The dispersions of the two coating materials were listed in Tables 1 and 2, which were obtained respectively from their single layer experiments under the same conditions with the harmonic beam splitter one. Considering the dispersions of the film materials, the one quarter wave layer for the center wavelength $\lambda_0$ was not a half wave layer for $\lambda_0/2$, then the basic film stack changed into a periodic one for $\lambda_0/2$ with periodic error which produced a reflective peak in the short-wavelength region, where the passband would be located. Figure 1 showed the theoretical performance of harmonic beam splitter with a half-wave hole, which located at about 0.532 $\mu$m. If the control wavelength adopted the half of center wavelength, the problem of dispersion at the half of the center wavelength would be eliminated, and the half-wave hole would disappear, which could be seen in Fig. 2, meanwhile, the transmittance at 1.064 $\mu$m would increase from 0.0072% to 0.009%, but this change was so little that could be acceptable. Then the basic stack transformed into the type: $(2H2L)^{13}$2HL.

From Fig. 2 we could see that there were still high ripples at about 0.532 $\mu$m, which would affect the transmittance at 0.532 $\mu$m. The low peaks of the ripples were due to the admittance mismatching between the basic stack and the adjacent media. Here a new admittance

**Table 1. The Dispersion of $Ta_2O_5$**

| Wavelength (nm) | 428 | 457 | 493 | 535 | 586 | 652 | 733 | 842 | 990 | 1202 |
|---|---|---|---|---|---|---|---|---|---|---|
| Refractive Index | 2.20 | 2.18 | 2.16 | 2.14 | 2.12 | 2.11 | 2.10 | 2.08 | 2.06 | 2.05 |

**Table 2. The Dispersion of $SiO_2$**

| Wavelength (nm) | 435 | 484 | 550 | 633 | 745 | 907 | 1064 | 1165 | 1315 | 1500 |
|---|---|---|---|---|---|---|---|---|---|---|
| Refractive Index | 1.52 | 1.51 | 1.50 | 1.49 | 1.48 | 1.47 | 1.47 | 1.47 | 1.47 | 1.47 |

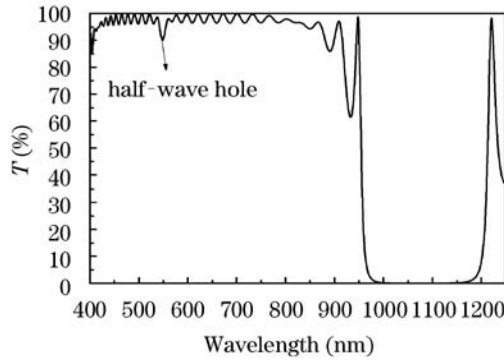


Fig. 1. Theoretical performance of beam splitter with a half-wave hole.

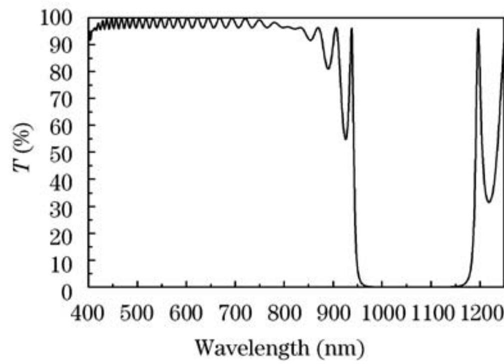


Fig. 2. Theoretical performance of beam splitter with high ripples.

matching method was used to resolve this problem. The basic stack was the subject of the matching procedure[7]. The matching of the basic stack with the adjacent media was obtained through intermediate symmetrically periodic structures using the same materials as the basic stack, situated between the basic stack and the adjacent media. The matching stack could have either the form $(a_m\text{H}\ b_m\text{L}\ a_m\text{H})^n$ or $(a_m\text{L}\ b_m\text{H}\ a_m\text{L})^n$. The equivalent refractive index of the matching stack $E_m$ must be equal to the geometrical mean of the basic stack equivalent index $E_b$ and the indices of the adjacent media. Simultaneously, another condition must be fulfilled: the phase thickness of the matching stack must correspond to an odd number of quarters of the matching wavelength. The following two equations are given as

$$E_{m1} = \sqrt{E_b \cdot n_0}, \quad E_{m2} = \sqrt{E_b \cdot n_\mathrm{s}}, \tag{1}$$

$$n\Upsilon = (2K+1) \cdot \frac{\pi}{2}, \tag{2}$$

where $n$ is the number of periods, $K$ =0, 1, 2, $\cdots$, and $\Upsilon$ is equivalent phase thickness.

The inverse problem is to obtain the phase thickness $\phi_a$ and $\phi_b$ for a structure $(aAbBaA)$ which provides the required equivalent refractive index $E_m$ and equivalent phase thickness $\Upsilon$. By computing the equivalent matrix for this structure and referring to the Ref. [8], the following three equations can be given as

$$\sin\phi_b = \left[\left(\frac{n_a}{E_m} - \frac{E_m}{n_a}\right) \Big/ \left(\frac{n_a}{n_b} - \frac{n_b}{n_a}\right)\right] \sin\Upsilon, \tag{3}$$

$$\cos\Upsilon = \cos 2\phi_a \cos\phi_b - \frac{1}{2}\left(\frac{n_a}{n_b} + \frac{n_b}{n_a}\right) \sin 2\phi_a \sin\phi_b, \tag{4}$$

$$\frac{1}{2}\left(\frac{n_a}{E_m} + \frac{E_m}{n_a}\right)\sin\Upsilon = \frac{1}{2}\left(\frac{n_a}{n_b} + \frac{n_b}{n_a}\right)\cos 2\phi_a \sin\phi_b + \sin 2\phi_a \cos\phi_b. \tag{5}$$

Depending on the values of $E_m$, $\Upsilon$, $n_a$, and $n_b$, this system provides for the unknown $\phi_a$, $\phi_b$ either a pair of solutions or none.

Here $E_b$ was equal to 1.81, so $E_{m1}$ and $E_{m2}$ should be 1.35 and 1.65 respectively. The matching stack was added only between the basic stack and the substrate media, but neglected between the basic stack and the air media to save depositing work. Following the method presented above and with a computer-aided film stack design procedure, the maximum number of twenty four solutions were obtained, with period number equal to or less than three ($n \leq 3$). In order to save work in operating, the proper solution was found to be $(3.7659\text{H}\ 1.4883\text{L}\ 3.7659\text{H}\ )^1$ with $n = 1$. Thus, the thin film structure had the form: Substrate/$(3.7659\text{H}\ 1.4883\text{L}\ 3.7659\text{H})^1(2\text{H}2\text{L})^{13}2\text{HL}$/Air.

Figure 3 showed the theoretical spectrum after matching. If the spectral region with high transmittance was narrow, a very accurate control of the layer thickness was necessary. In order to relax the requirements for the control accuracy, efforts were made to obtain a designing film stack providing a wider region with high transmittance. Meanwhile, a favorable layer sensitivity of stack was required. The stack's layer thickness varied by relative 2% and refractive index varied by 2% for all layers independently, which indicated that the stack's tolerance error was satisfying. Figure 3 indicated that this stack could meet these requirements. The theoretical transmittance was 99.76% at 0.532 $\mu$m and 0.0057% at 1.064 $\mu$m, and the minimum was 99.22% in the range from 0.49 to 0.55 $\mu$m.

This harmonic beam splitter was sputtered by two RF ion beam sources: one was a 16-cm primary source, and the other was a 12-cm ion assisted source. Figure 4

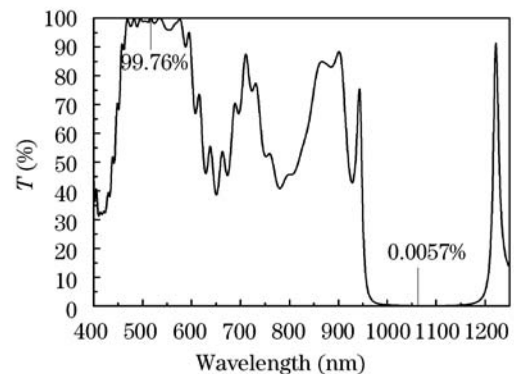


Fig. 3. Theoretical performance of beam splitter after matching.

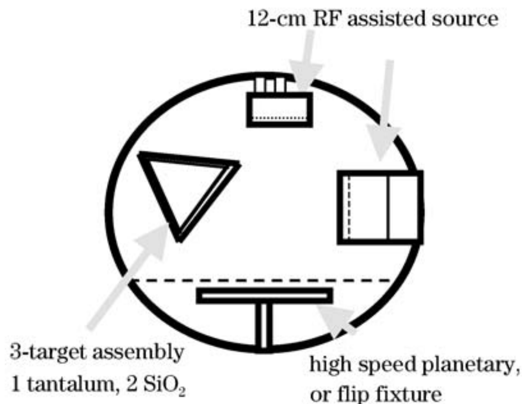


Fig. 4. Schematic of the RF ion beam sputtering coating system.

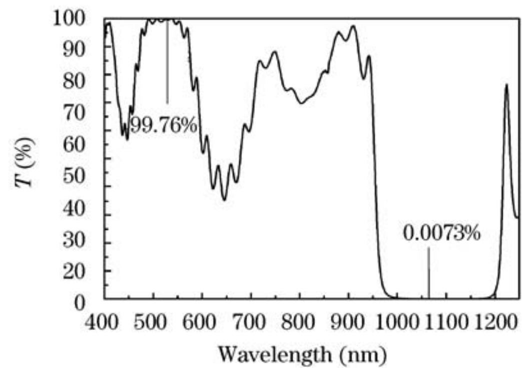


Fig. 5. Experimental performance of beam splitter.

showed the setup of the deposition apparatus. Prior to the deposition run, the sputtering chamber was cryogenically pumped to a base pressure below $2.66\times10^{-6}$ Pa. The substrate was baked to 300 °C. Ar and $O_2$ were introduced to the RF ion beam sources and target. The flow volume of Ar was 48 sccm for primary source, 5 sccm for RF neutralizers. The ratio of $O_2$ and Ar for ion assisted source was 4:1 (12 to 3 sccm), the flow volume of $O_2$ was 25 sccm for target, which was used to react with tantalum to form $Ta_2O_5$ and prevent the deviation from stoichiometry. Target consisted of tantalum and silicon oxide (99.99%). Its area (32 $cm^2$) was larger than that of the ion beam so that the fixture would not be sputtered to contaminate the system.

The physical thickness of the beam splitter was obtained from the stack with half-wavelength control. It was controlled by time-power method, which was based on the fact that there was a sufficiently constant rate of deposition of physical thickness. The sputtering rates were 0.28 nm/s for $Ta_2O_5$ and 0.23 nm/s for $SiO_2$. To increase the mechanical and laser radiation resistance ability of the sample, the substrate was cleaned with acetone in ultrasonic cleaner at room temperature before deposition. The optical property of the sample was characterized with a Lambda 900 spectrophotometer.

Figure 5 presented the experimental performance of the beam splitter. The measured transmittance was 99.58% at 0.532 $\mu$m and 0.0073% at 1.064 $\mu$m, the average was 99.51% for the passband from 0.505 to 0.543 $\mu$m, so the splitting ratio was equal to $7.3\times10^{-5}$. The back of substrate was deposited with antireflection coating for 0.532 $\mu$m to eliminate the reflectance of the second side of the substrate, and a good agreement between the experimental and theoretical curves was obtained. Whereas, the experimental passband became little narrower, which was probably due to the thickness increasing of final few layers with the slight increasing of the sputtering rates. But this change of thickness probably just achieved better matching, which led to preferable transmission effect, i.e. the passband became smoother. The layer thickness control error precision of the RF ion beam sputtering coating system was 0.5% and it is far lower than the tolerance error of the film stack, so the experimental results was perfect. It is worthwhile to mention that the RF ion beam sputtering avoided such system error as being caused by compensating effect and the artificial error for photoelectric maximum method.

A harmonic beam splitter deposited on a BK7 glass substrate and to be used in optics working with a Nd:YAG rod was designed and realized. A computer-aided admittance matching method was used, which effectively smoothed high ripples in the transmittance region. The control wavelength adopted the half of center wavelength, which avoided the problem of dispersions of film materials and eliminated half-wave hole fundamentally. The obtained experimental performance showed a good agreement with the theoretical results.

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