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Studies on the characteristics of laser beams' coherent summation by grating☆

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Abstract

Experimental studies on laser beams' coherent summation by grating are described in this article, including the combination efficiency, the quality of the combined beam and the robustness of the beam combination system. The measured three He–Ne beams' combination efficiency is greater than 60% with the far field M^2 about 1.3. The experimental studies show that if using an uniform splitter as a combiner in the equal strength laser beams' combination, when some of the laser units spoiled, the change of the combination efficiency simply equals the ratio of the number of the damage laser units to the total number of the laser units to be combined, and the wave-front of the combined beam still keeps good shape. The investigations introduced in this paper show that laser beams' coherent summation by grating can fulfill its task well with high combination efficiency, excellent combined beam quality and good robustness.

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1. Introduction

High power laser beams are necessary in many fields, such as the next-generation laser communication in free-space, etc. But the growth of the output power of a single laser tube is always limited by the gain saturation, and in the solid- and the gas-laser units, the optical damage to the facet is also an important limitation for the improvement of the output power. So, it is a worthy attempt to combine many laser beams coherently together to enlarge the total output power of the laser system [1–4].

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The preconditions of the laser beams' coherent summation are that the phases of each laser beam are locked and matched with one another. These can be realized by some special method [1,2]. The main purpose of this paper is to investigate the characteristics of laser beams' coherent summation by grating under these preconditions. So in the following studies, we will simulate three laser beams by splitting one beam into three. Obviously, this arrangement can ensure satisfying the above preconditions all along within the entire experimental process, and reveal the nature of laser coherent combination in greater precision.

2. Theoretical descriptions

Fig. 1 is a sketch of a grating structure and the selection of the reference frame.

It is easy to obtain the expression of the combination efficiency within the frame of the scalar diffraction theory. The transmittance function of a grating can be expressed as

$$t(x) = \sum_{n=-\infty}^{+\infty} a_n \exp(\mathrm{i}\phi_n) \cdot \exp(\mathrm{i}n\alpha x), \quad (1)$$

where, a_n stands for the amplitude of the nth diffraction order. Furthermore, $a_n = f(n) \cdot a_0$. Here a_0 stands for the amplitude of the 0th diffraction order. $f(n)$ is determined by the given grating structure, and $f(0) = 1$. When the $N+1$ laser beams with suitable phases relationship pass through the grating along the inverse directions of the $-N/2,\ldots,N/2$ diffraction orders, the strength of the 0th transmit light can be expressed as

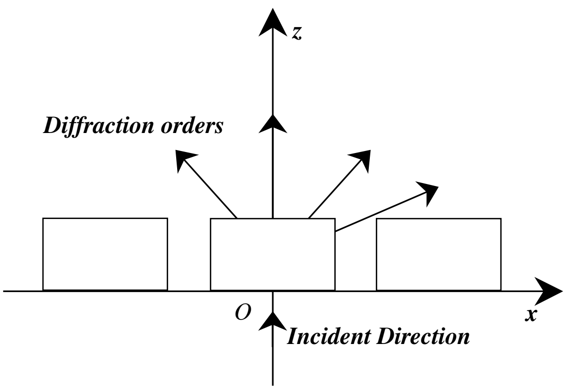

Fig. 1. Sketch of a grating structure and the selection of the reference frame.

$$I_0 = \left| \sum_{n=-\frac{N}{2}}^{+\frac{N}{2}} [g(-n) \cdot f(n)] \right|^2 \cdot |a_0|^2, \quad (2)$$

where, $g(n)$ is the modulus of the incident beam's amplitude located at the nth diffraction order, $n = -N/2,\ldots,N/2$. Then the combination efficiency is obtained

$$\eta_{\mathrm{cmb}} = \frac{\left| \sum_{n=-N/2}^{N/2} [g(-n) \cdot f(n)] \right|^2}{\sum_{n=-N/2}^{N/2} |g(n)|^2} \cdot |a_0|^2. \quad (3)$$

For a uniform splitter, one can have

$$f(n) = 1, \quad \left(n = -\frac{N}{2}, \ldots, \frac{N}{2}\right).$$

So Eq. (3) can be rewritten as

$$\eta_{\mathrm{cmb}} = \frac{|\sum g(n)|^2}{\sum |g(n)|^2} \cdot |a_0|^2. \quad (4)$$

For a three beam coherent combination, if $\gamma_{\pm 1} = g(\pm 1)/g(0)$, Eq. (4) can be expressed as

$$\eta_{\mathrm{cmb}} = \frac{(1 + \gamma_{+1} + \gamma_{-1})^2}{1 + \gamma_{+1}^2 + \gamma_{-1}^2} \cdot |a_0|^2. \quad (5)$$

Furthermore, if $\gamma_{-1} = \gamma_{+1} = \gamma$, one has

$$\eta_{\mathrm{cmb}} = \frac{(1 + 2\gamma)^2}{1 + 2\gamma^2} \cdot |a_0|^2, \quad (6)$$

where, a_0 stands for the amplitude of incident beam located at the 0th diffraction order. Fig. 2 shows the changes of the combination efficiency varying with γ.

From the figure one can see that when $\gamma = 1$, the combination efficiency reaches its summit; when γ is smaller than 1, the combination efficiency reduces rapidly to $|a_0|^2/3$ with γ's departure from 1. In this case, the grating acts as a splitter. But when γ is greater than 1, the reduction of the combination efficiency is slow.

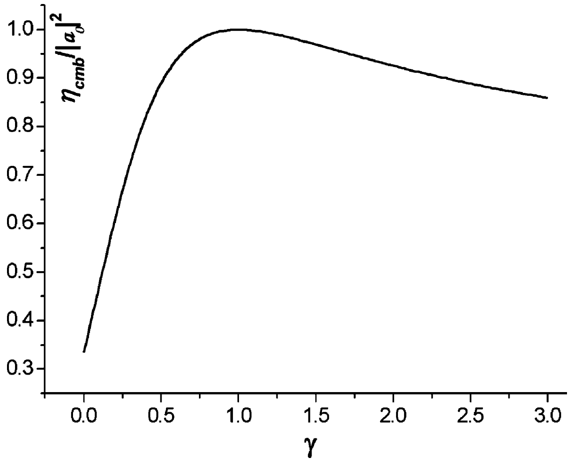

Fig. 2. Influence of the relative amplitude of split beams to the combination efficiency when combining equal strength beams.

If some of the laser tubes are damaged during beam combination, say tubes located at (*i*,*j*,*k*,...)th diffraction order (totally *m* tubes), the combination efficiency to be realized can be obtained from Eq. (3)

$$\eta'_{\mathrm{cmb}} = \frac{\left|\sum\limits_{n\neq(i,j,k,\ldots)} [g(-n)\cdot f(n)]\right|^2}{\sum\limits_{n\neq(i,j,k,\ldots)} |g(n)|^2}\cdot |a_0|^2, \tag{7}$$

i.e.

$$\frac{\eta'_{\mathrm{cmb}}}{\eta_{\mathrm{cmb}}} = \frac{\left|\sum\limits_{n\neq(i,j,k,\ldots)} [g(-n)\cdot f(n)]\right|^2}{\left|\sum\limits_{n} [g(-n)\cdot f(n)]\right|^2} \times \frac{\sum\limits_{n} |g(n)|^2}{\sum\limits_{n\neq(i,j,k,\ldots)} |g(n)|^2}. \tag{8}$$

So, when using a uniform splitter as a combiner for equal strength laser beams' coherent summation, Eq. (8) can be simplified as

$$\frac{\eta'_{\mathrm{cmb}}}{\eta_{\mathrm{cmb}}} = \left(\frac{N+1-m}{N+1}\right)^2 \times \frac{N+1}{N+1-m} = \frac{N+1-n}{N+1}, \tag{9}$$

where, *m* is the total number of the damaged laser tubes.

3. Experiments

The experimental setup is shown in Fig. 3. He–Ne light passes through a polarizer before being split into three. The middle one is incident on the grating along the direction of the 0th diffraction order and the other two are incident along the directions of ±1th diffraction order of the grating, respectively, after being reflected by the mirrors adhered to piezos. The relative phases of the three incident beams are adjusted by these two piezos. The combined beam shines a screen or injects into a detector.

Here, the fabrications of the beam splitter grating and the combination grating are the same. They are all binary phase gratings with equal intensity strengths of 0th and ±1th diffraction orders. They are made by ion beam etching on a quartz substrate and are AR coated to minimum the light losses [5].

The experimental results are listed in Table 1. It can be seen that the combination efficiency of the TE polarized wave is slightly bigger than that of the TM wave. Here, the differences between the measurements and the theoretical predictions are slightly large, they come from the measurement errors and that the strength- and phase-relationship of the incident beams do not meet the needs of the beam combination by the grating fully.

From Table 1, one can see that when some of the laser units spoiled during combining, the losses of the measured combination efficiencies are nearly satisfied to the theoretical predictions, namely

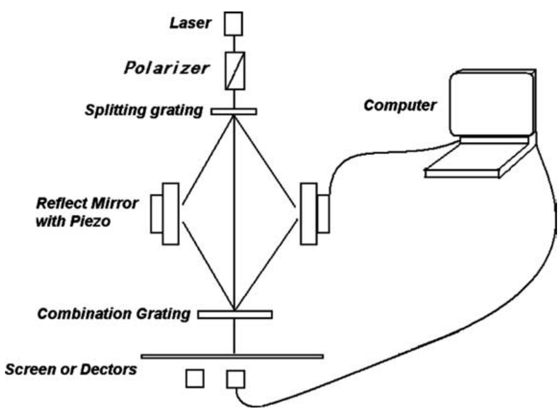

Fig. 3. Experimental setup.

Table 1
Experimental results of M^2 and combination efficiency of the combined beam under various situations (for TE/TM polarized beams)

	Incident laser beam strength (×0.5 mW)	Splitting efficiency (%)	No laser unit spoiled		Laser unit spoiled	
			Combination efficiency (%)	Far-field M^2	Current combination efficiency (%)	Current far-field M^2
A					43.33/38.43	1.36/1.34
						1.30/1.19
	1.56/1.17/1.59	71.13 (24.70/20.86/25.57)	62.58	1.34/1.20	49.37/44.92	1.33/1.35
	1.71/1.37/1.78	70.51 (24.29/21.77/24.45)	56.94	1.41/1.09		1.17/1.04
					42.06/40.45	1.16/1.28
						1.26/1.05
B					45.91/43.62	1.41/1.42
						1.36/1.29
	2.05/1.57/1.96	75.87 (26.54/24.73/24.60)	61.91	1.38/1.34	40.29/38.38	1.44/1.46
	1.06/1.23/0.99	74.93 (24.89/25.41/24.63)	58.47	1.39/1.51		1.18/1.32
					48.30/42.26	1.36/1.52
						1.26/1.25
C					39.22/37.76	1.59/1.49
						1.62/1.46
	1.37/1.32/1.39	82.95 (30.47/21.32/31.16)	63.23	1.51/1.70	47.25/44.31	1.49/1.40
	0.77/0.75/0.80	82.06 (26.39/30.47/25.19)	56.49	1.42/1.26		1.30/1.42
					39.77/44.25	1.52/1.50
						1.62/1.54

(i) In the first column, 'A' stands for the combination type in which the relationships of the incident beams fit for the best incident conditions of the combiner; 'B' stands for the combination type in which non-equal strength beams are incident on a uniformity grating; 'C' stands for the combination type in which equal strength beams incident on a non-uniformity grating.

(ii) In the 'splitting efficiency' column, the top numbers are TE and the bottom ones TM, and data in the bracket stand for the splitting efficiencies of the −1/0/+1 diffraction orders, respectively.

(iii) In the column 'Incident laser beam strength', the top data are TE and the bottom ones TM, and data separated by '/' stand for the laser beam strength located on the −1/0/+1 diffraction orders, respectively.

(iv) In the column 'far-field M^2', data in the first line stand for the M^2 in the *x*-, *y*-direction of TE polarized wave and data in the second stand for that of TM.

(v) In the column 'Laser unit spoiled', the three rows stand for the case that the spoiled laser unit is located on the −1/0/+1 diffraction order, respectively. Data separated by '/' correspond to TE/TM and data in 'current far-field M^2' are values of the *x*-direction (top numbers) and the *y*-direction (bottom numbers) for TE/TM polarized waves, respectively.

equal to the ratio of the number of the damage laser units to the total number of the laser units to be combined. Also, the M^2 values for the combined beams in both *x*- and *y*-directions are small under various situations. These clearly show that the shapes of the wave-fronts of the combined beams' are good, almost are of the Gaussian shapes.

4. Conclusion

By splitting a He–Ne laser beam into three to simulate three laser beams with matched frequencies and phases, theoretical and experimental studies have been done to the capabilities of the method of laser beams' coherent summation by grating, including the combination efficiency, the quality of the combined beam, the robustness of the combination system, etc. According to the theoretical analyses, in the ideal situation, the beam splitting efficiency equals the beam combination efficiency. This means that the designation of the splitter with high splitting efficiency and good splitting uniformity is very important for fulfilling the task of the laser beams' coherent summation. Also, when some of the laser units are spoiled during combining, the change of the efficiency simply equals the ratio of the number of the damage laser units to that of the total laser units, and the combined beams' wave front keeps in good shape.

The experimental results show that the method of beams' coherent combination by grating can fulfill its task well with high combination efficiency, fine quality of the combined beam and excellent robustness of the combination system.

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