

Coherent summation of laser beams using binary phase gratings

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A method for coherent addition of lasers is presented that uses binary phase-only gratings. It is shown that a grating that splits a single beam into N equal orders with high efficiency can be used in reverse to convert N laser beams into a single beam with the same efficiency. Experiments to demonstrate the conversion of seven beams to one beam are performed with a resulting conversion efficiency of 75%. An experimental apparatus is described that adds the power from both two and three He-Ne lasers (wavelength, $3.39\ \mu\text{m}$) with efficiencies as high as 83%.

Many laser systems are limited in practical output power by a specific physical mechanism. For example, a restriction on the cross-sectional area of the lasing medium is often necessary when single-spatial-mode operation is required. In addition, some semiconductor lasers, such as GaAs, are limited in power by output facet damage, which occurs at high light intensities. Other semiconductor lasers are primarily restricted to low output power by heat removal limitations.

The parallel coherent addition of laser beams offers a new way around the above limitations. The aim is to generate laser power in many modular lasing elements and combine their outputs in parallel to produce a single, more powerful beam. In this Letter we describe a method of combining laser beams that utilizes a binary phase-only diffraction grating both to establish the coherence between the lasers and to couple the multiple beams into a single Gaussian beam.

To achieve efficient coupling of N laser beams into a single beam, the grating is designed to have an impulse response that consists of N large and approximately equal diffraction orders, with the remaining orders containing little power. The transmittance of the grating can be expressed as a superposition of plane waves corresponding to the diffraction orders of the grating:

$$t(x) = \sum_{n=-\infty}^{\infty} a_n \exp(j\phi_n) \exp(jn\alpha x), \quad (1)$$

where a_n and $\exp(j\phi_n)$ are the magnitude and the phase of the n th plane-wave component and α is proportional to the sine of the angle between diffraction orders. The grating is designed such that $a_n \approx a_0$ for plane waves between $-N/2$ and $N/2$. (N is assumed to be even in this derivation.) The splitting efficiency ζ is defined as the amount of power contained in the $N+1$ desired orders compared with the total incident power:

$$\zeta = \sum_{n=-N/2}^{N/2} a_n^2 \approx (N+1)a_0^2. \quad (2)$$

Gratings with high splitting efficiencies and equal diffraction-order intensities can be designed by proper location of the transition points within a single period of the binary phase grating.^{1,2}

Coherent addition of laser beams can be accomplished by operating this grating in reverse. The grating is illuminated with $N+1$ laser beams at angles corresponding to the original grating diffraction orders. The laser beams have unity amplitude, and their phases are chosen to be the complex conjugates of the original diffraction orders. The interference pattern of these beams in the plane of the grating is then given by

$$E(x) = \sum_{m=-N/2}^{N/2} \exp(-j\phi_m) \exp(-jm\alpha x), \quad (3)$$

where the Gaussian profile of the laser beams is unimportant to the derivation and is not included.

The amplitude of the light after passing through the grating is given by the product of Eqs. (1) and (3). The cross terms that result represent all the plane waves leaving the grating. The on-axis plane waves correspond to the terms where $m = n$. The intensity in the zeroth diffraction order of the grating is given by the square of the coherent sum of these on-axis plane waves:

$$I_0 = \left| \sum_{n=-N/2}^{N/2} a_n \right|^2 \approx (N+1)^2 a_0^2, \quad (4)$$

since $a_n \approx a_0$ when $-N/2 \leq n \leq N/2$.

The efficiency η with which the power of the $N+1$ laser beams is coupled into the central order of the grating can be defined as the ratio of the zero-order grating intensity to the incident intensity. Since the $N+1$ lasers each have unit intensity, this ratio is given by

$$\eta = \frac{(N+1)^2 a_0^2}{(N+1)} = (N+1)a_0^2. \quad (5)$$

It is apparent from Eqs. (2) and (5) that the splitting

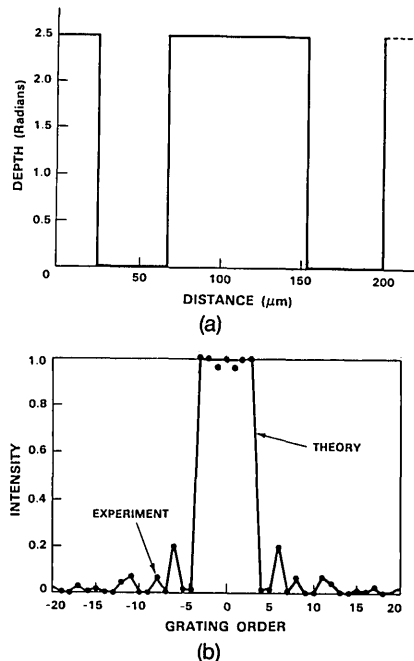


Fig. 1. (a) Single period of the grating for adding seven lasers. The grating consisted of a replication of this pattern. (b) Diffraction pattern produced by grating in (a).

and combining efficiencies are identical for these gratings.

The effect of laser failure on total output can be calculated from Eq. (4). If L lasers have failed, the intensity in the zeroth diffraction order becomes

$$I_0' = \left| \sum_{\substack{n=-N/2 \\ n \neq 1, 2, \dots, L}}^{N/2} a_n \right|^2 \approx (N+1-L)^2 a_0^2, \quad (6)$$

and the new coupling efficiency is given by

$$\eta' = (N+1-L)a_0^2. \quad (7)$$

The reduced intensity in the output of the beam combiner from expression (6) is seen to be the product of the lower coupling efficiency in Eq. (7) and the reduced intensity from the smaller number of laser sources $(N+1-L)$.

In order to test the splitting and combining properties of gratings, a binary phase grating was designed to split a He-Ne beam into seven orders of roughly equal intensity. The internal structure of a grating period and the phase depth were computed to give the desired response and are shown in Fig. 1(a). A grating consisting of many replications of this unit cell transmittance was manufactured by etching a quartz substrate to the proper depth using reactive ion-etching techniques. Figure 1(b) shows the result of passing a single He-Ne beam (wavelength, $0.633 \mu\text{m}$) through the grating. The diffraction pattern is compared with the theoretical pattern calculated by a computer using the Fourier diffraction equations. The theoretical splitting efficiency of this grating is 84.5%. A splitting efficiency of 80% was measured.

A second grating was made with an identical profile

but with a depth corresponding to the complex-conjugate phase. The seven beams generated by the first grating were used to simulate seven laser sources by passing them through a rectangular aperture to eliminate all higher orders. These sources were already coherent with respect to one another and had the correct phase relationships for beam combining. The ability of the conjugate grating to convert these sources into a single Gaussian beam was tested by redirecting the seven beams with a lens so that they interfered with one another at the plane of the conjugate grating. Figure 2 shows measurements of the

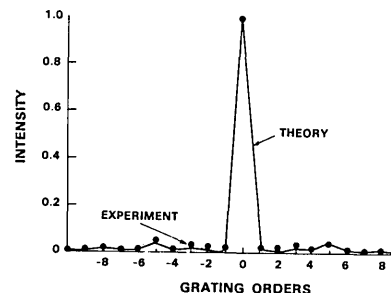


Fig. 2. Angular plane-wave spectrum of light field as it leaves the combining grating. The coupling efficiency can be calculated by computing the ratio of power in the central order to the total power in all the orders.

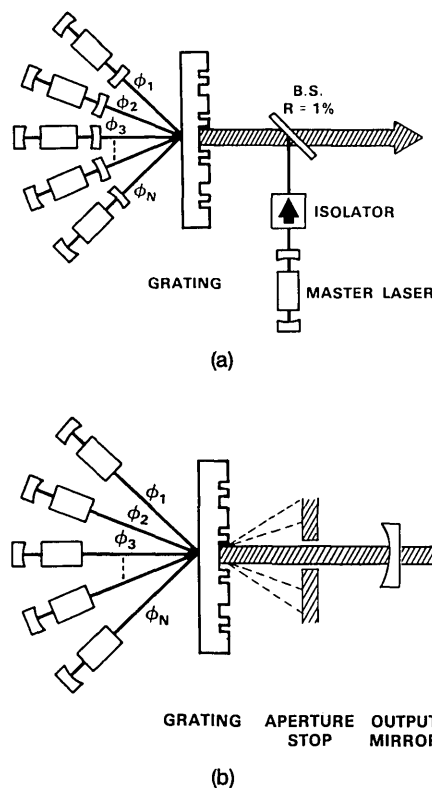


Fig. 3. Two configurations to achieve coherent beam addition. (a) A master oscillator is used to injection lock the slave lasers. The grating is used in reverse to split the master oscillator beam into N locking beams. (b) A common-cavity configuration is used, and the grating is placed inside the cavity.

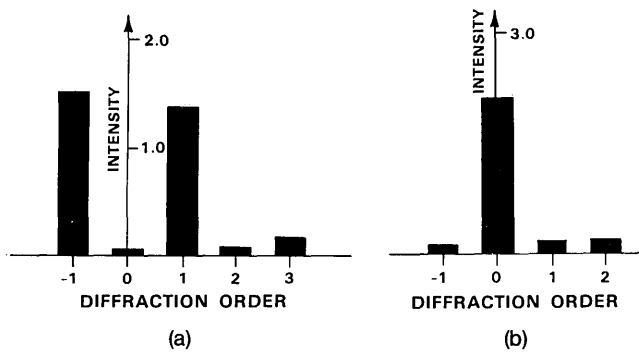


Fig. 4. (a) Impulse response of the grating designed to combine two He-Ne lasers. The orders to the left of -1 are all evanescent. The splitting efficiency was measured to be 90%. (b) The angular plane-wave spectrum of the combined He-Ne laser beams. 83% of the power is contained in the zero-order Gaussian beam.

angular plane-wave spectrum of the resultant light field. The measured coupling efficiency was 75%, whereas the theoretical coupling efficiency was 84.5%. The discrepancy was due to inaccurate etching depths in the two gratings.

In order to add several discrete lasers, coherence and proper phase relationships between the lasing sources must be established for efficient combining by the phase grating. This can be accomplished in either of two ways. One method uses a master oscillator laser to injection lock the slave lasers, as shown in Fig. 3(a). In this configuration, the same grating that performs the beam combining is used in reverse to split the master laser into N equal-strength locking beams. A second method uses a common output mirror with the grating inside the cavity, as shown in Fig. 3(b). If the lasers are not coherent with respect to one another or if the phase relationships are not correct, the coupling into the zero order of the grating will be small. This results in a low feedback from the output mirror. The lasing condition with the lowest threshold is achieved when the output-mirror feedback is highest, that is, when the lasers are coherent and phased correctly for maximum coupling efficiency.

Experiments were performed to add laser beams from both two and three He-Ne lasers using the common-cavity configuration of Fig. 3(b). The lasers were designed to lase at the $3.39\text{-}\mu\text{m}$ line because of its high gain. Piezoelectric mounts were provided on the end mirrors for cavity-length control. The gratings had relief profiles that were 50% duty cycle square waves. For adding two lasers, the phase depth of the grating was chosen to be π rad, and lasers were placed at the ± 1 diffraction orders. In this simple case, the interference of the two lasers produced a sine wave amplitude, and the grating performed the rectification of this sine wave. Correspondingly, the coupling effi-

ciency for two-laser addition was identical to the familiar full-wave rectifier power-conversion efficiency of 81%. The optimal phase depth for adding three lasers is given by $2 \arctan(\pi/2) = 2.0078$ rad. At this depth, the contribution of the zero-order beam is exactly equal to the $\pm$ first-order beams. The theoretical coupling efficiency of the grating was 86.5%.

The gratings were designed to be used in the reflection mode with an incidence angle of 45° . Both gratings had a periodicity of $21.4\text{ }\mu\text{m}$. The impulse response of the grating designed to add two lasers is shown in Fig. 4(a). In this case, all diffraction orders less than -1 were evanescent. Orders greater than $+3$ were very small. The splitting efficiency was measured to be approximately 90%. This is significantly higher than the theoretical prediction, since evanescent orders are not accounted for in the theory.

The coupling efficiency was measured by inserting a low-reflectivity beam splitter directly after the grating in the common-cavity configuration [Fig. 3(b)]. A small amount of light was reflected out of the cavity, and the power in each of the diffraction orders was measured. Figure 4(b) shows the result when two lasers are added. Approximately 83% of the total power is contained in the central order.

Laser-failure response was measured by combining three He-Ne laser beams and blocking one of the beams to simulate a laser failure. Blocking the center laser reduced the power to 40% of the original. Using expression (6), the expected power reduction resulting from the failure of one of three lasers is 44%. With the grating inside the laser cavity, however, the nonlinear gain coefficient of the cavity affects the power, and the output is somewhat less.

In summary, a method for combining laser beams coherently has been presented. It was shown that binary phase-only gratings could be designed to perform efficient coupling of N laser beams into a single beam. This principle was demonstrated using two gratings and a single He-Ne laser. Finally, the outputs of both two and three He-Ne lasers were coupled with high efficiency into a single laser beam using a reflective binary grating.

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