Laterally periodic resonator for large-area gain lasers

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Abstract: Laterally periodic resonators, which can be constructed by use of transversely periodic phase- or amplitude-modulating elements in a cavity, are proposed for stabilization and generation of transversely coherent output from large-area gain. Lasers with periodic resonators have the combined features of conventional cavities and laser arrays. Significant low-order transverse modes and mode discrimination of a sample resonator with intracavity periodic phase elements are investigated numerically by the iteration method. Wave-propagation calculations are carried out by use of a fast Fourier transform, and a modified Prony method is used to evaluate wave functions and losses of transverse modes. Results of numerical calculations are consistent with expectations.

OCIS codes: (140.3410) Laser resonators; (140.3290) Laser arrays

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1. Introduction

Although energy storage can be enhanced by use of large-volume gain media, generation of high laser-output power from conventional stable resonators, while maintaining good beam quality, is limited by fundamental Gaussian-mode volume and by the problem of damage from cavity elements. To extract available power from large-area gain, unstable resonators with graded reflective mirrors have been successful [1] but are not suitable for low- and medium-gain lasers. Another approach is use of the master oscillator power amplifier (MOPA) [2,3], which has a low-power but high-beam-quality laser as a master oscillator and large-area gain media as amplification stages. Hence MOPA combines the advantages of high beam quality with MO and the high energy storage of amplifiers. However, this system is complicated, and its efficiency is generally low.

The broad-area laser (BAL) is a type of large-area gain laser in the field of semiconductor lasers, which has received both theoretical and practical attention [4-8]. To suppress the chaotic spatiotemporal filamentation and to generate stable and coherent output, the above-mentioned unstable resonators and MOPA have been used. In addition, BALs with single or several profiled reflecting stripes have been investigated [5,8,9]. It has been shown that the BAL could be an effective tool for lateral mode control; moreover, stabilization of the filament location was obtained. Another interesting approach is the so-called "custom resonator," which enables the custom fundamental mode profile by use of a diffractive mode-selecting mirror and intracavity phase plates [10-12] but gives good results only for cavities with quite small Fresnel numbers. However, phase locking of multiple laser outputs, as an alternative approach for scaling output power while maintaining beam quality, has been intensively investigated for semiconductor lasers [13-17], fiber and planar waveguide lasers [18-20], solid-state lasers [21-24], CO_2 lasers [25], and so on. Three coupling mechanisms exist: evanescent coupling, in which gain cores couple evanescently to their nearest neighbors; diffractive coupling, such as Talbot plane methods; and radiative coupling, in which all gain cores communicate with all others, such as antiguided laser arrays. Because of phase locking, optical fields would be confined mostly to one or two lobes for in-phase and out-of-phase locking, respectively.

In this paper, a laterally periodic resonator is proposed for generating coherent output from large-area lasers. As shown below, such a design combines some features of large-area lasers and phase-locked laser arrays. Differences between this approach and previously reported ones are discussed. Modal properties of a sample laterally periodic resonator are investigated numerically.

2. Concept

The Fresnel number plays a similar role in optics as the Reynolds number does in hydrodynamics [26]. Multimode operation and even spatiotemporal filamentation will occur in lasers with large Fresnel numbers. Our concept is based on combining features of broad-area lasers and laser arrays. The laterally periodic resonator, which can be constructed by use of transversely periodic phase- or amplitude-modulating elements in a cavity, could be considered physically as an array of equally separated identical subresonators, if diffractive coupling between oscillations of subresonators is not too strong (as with the tight binding approximation in solid-state physics). Let the Fresnel number of the whole resonator be N_f, and the period number, m; then the Fresnel number of the subresonators is $\sim N_f/m$. If N_f/m is small enough (sufficiently small N_f/m can always be obtained by means of choosing a sufficiently high m value), subresonators alone are likely to generate stable and high-beam-quality outputs. Because of coupling between them, oscillations in these subresonators can be locked together. Hence coherent output from all subresonators, which means coherent output from large-area gain, is possible. This is the key point of the current concept. Thus techniques and insights from phase locking of an array can be applied to this situation.

The difference between this concept and that of common laser arrays is that, here, gain is uniform over the cross section instead of being spatially distributed. So obviously, this concept has the advantage of ease in fabrication of gain medium compared with multicore waveguide laser designs [18-20].

However, when diffractive coupling between subresonators is strong, previous laser array approximation is no longer valid, and the laser resonator should be considered as a whole (as a nearly-free-electron approximation in solid-state-physics). But even in this case, the question of whether laterally periodic feedback has a good effect on suppressing the spatiotemporal filamentation and on generating coherent output from large-area gain has yet to be answered.

It is noteworthy that in this case the current concept is similar to previously reported approaches, such as custom resonators and resonators with intracavity binary phase elements [10]. But since those approaches all aim at generating a custom mode from a conventional cavity with a certain axial symmetry, limited application on small N_f is inevitable. However, since the current concept is based on periodic structure, no limitation on lateral dimension is expected *a priori*, at least theoretically.

Modal properties of laterally periodic resonators should have features of both laser arrays and conventional resonators. In the region of "tight binding approximation," coupled-mode theory can be applied [27,28]. When the coupling strength is larger, a more rigorous theory is needed. Three sets of indices are possibly required for designating resonant modes: One originates from the corresponding cavity without a periodic phase plate, one originates from the periodic feature of a cavity, and one originates from modes of subresonators. Research on analytical description of modes is not included in the paper; instead, numerical investigations of a sample resonator are presented here to give the main physical properties as a first step.

3. Modal properties of an example resonator

3.1 Numerical model

Figure 1 illustrates the sample resonator configuration. The modulated feedback could be of either phase or loss. In practice, loss modulation can be realized by modulated reflection coating or insertion of a lossy filter. By inserting a phase plate, we can realize phase modulation. For the sake of mathematical simplicity, cosine phase modulation is considered here.

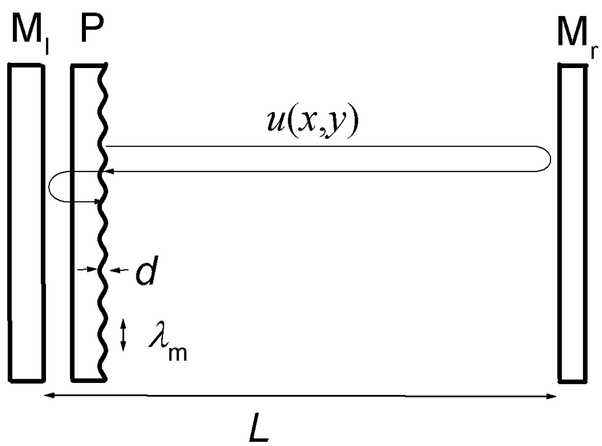

Fig. 1. Schematic of the introductory resonator configuration used in numerical investigation. M_l, M_r, and P are left end mirror, right end mirror, and periodic phase plate, respectively. L is cavity length; d and λ_m are modulation depth and spatial period of P, respectively. $u(x,y)$ is the optical field oscillating in the cavity.

To evaluate modes and their losses, the iteration method first introduced to mode calculation by Fox and Li is applied [29]. A fast Fourier transform (FFT) is used for wave-propagation calculations, which was first introduced by Siegman and Miller [30] for its significant increase in computational efficiency. The difference and key element here is the periodic phase plate. Assuming that the phase plate P is placed close to the plane mirror M_l, passing twice through the grating amounts to multiplying the field distribution $u(x,y)$ by a laterally periodic phase delay of twice the modulation depth d:

$$u(x,y) = u(x,y)\exp\left[j2d\cos\left(\frac{2\pi\sqrt{x^2+y^2}}{\lambda_m}\right)\right], \tag{1}$$

where d is the phase-modulation depth and λ_m is the modulation spatial period.

The Prony method is used to find low-order transverse modes and their associated losses [31]. Calculations using this method give higher precision for the modes that have lower loss. So only modes with the lowest loss are picked up; then another iteration is started with a new initial field distribution, which is orthogonal to all mode functions that have already been selected. Our calculations show that such a modified Prony method results in much better precision.

Thus data pairs $\{\gamma_i, u_i(x,y)\}$ can be obtained, where γ_i is the resonator eigenvalue, which relates to the round-trip loss of the ith mode of the bare cavity by $1 - |\gamma_i|^2$ and $u_i(x,y)$ is the field distribution of the ith mode. The far-field intensity pattern can be calculated by means of squaring the Fourier transform of the corresponding mode field. When applying the FFT method in wave-propagation calculation, we must pay careful attention to questions of aliasing, sampling, and windowing.

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3.2 Results and discussion

Numerical investigation was performed on a one-dimensional model. λ was set to 1 μm, λ_m was set to 1 mm, a phase plate with 10 periods of modulation was inserted into a plane–plane cavity, and the mirror diameter was 10 mm. Cavity length L and modulation depth d were two varying parameters for investigation.

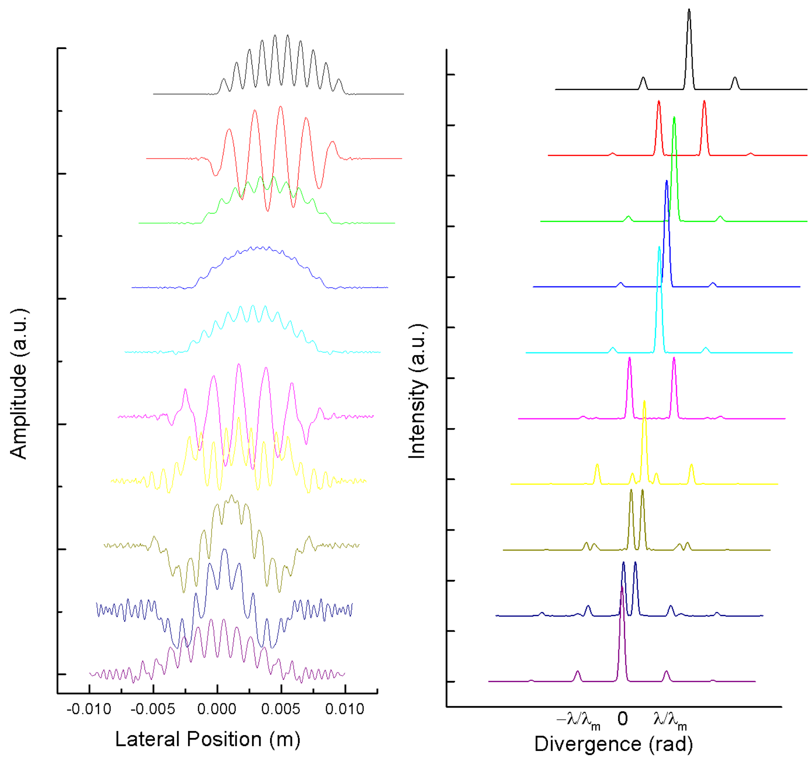

Fig. 2. Left, fundamental mode patterns for resonators with modulation $d = \pi/8$ and cavity length $L = 0.125, 0.250, \ldots, 1.25$ from top to bottom, respectively. Right, corresponding far-field patterns.

By starting with a random initial optical-field distribution, the optical field always becomes symmetric and coherent across the lateral section after a sufficiently large number of iterations, which means that the diffractive coupling among different portions of the cavity would always be strong enough to give rise to spatial coherence. This phenomenon is a numerical artifact and should not be occur for real cavities that have losses, gains, and perturbations. There must be a requirement on coupling strength for the optical field across the lateral section to be correlated.

The fundamental mode structures for several different cavity lengths and for $d = \pi/8$ and the corresponding far-field patterns are displayed in Fig. 2. The longer the resonator, the larger the coupling between subresonators. One can see that modal structures are quite diverse. At the vicinity of $L = 0.125$ m and 1.25 m, fundamental modes are in-phase beam arrays; at $L =$ 0.25 m and 0.75 m, fundamental modes are out-of-phase beam arrays; at the neighborhood of $L = 0.5$ m, which is one quarter of a Talbot length, the beam profiles of fundamental modes are similar to fundamental Gaussian modes of corresponding empty resonators but with extra modulations. This is because of the Talbot effect [32]. A periodic beam will image itself with a laterally half-period shift after propagating through half the Talbot length, $2\lambda_m^2/\lambda$, which is one round-trip in this case. So the spatial phase modulation induced by the periodic phase plate is somewhat compensated, and the effect of the periodic phase plate is reduced. At $L = 1.0$ and

1.125 m, envelopes of fundamental modes correspond to the third mode of the corresponding empty cavity.

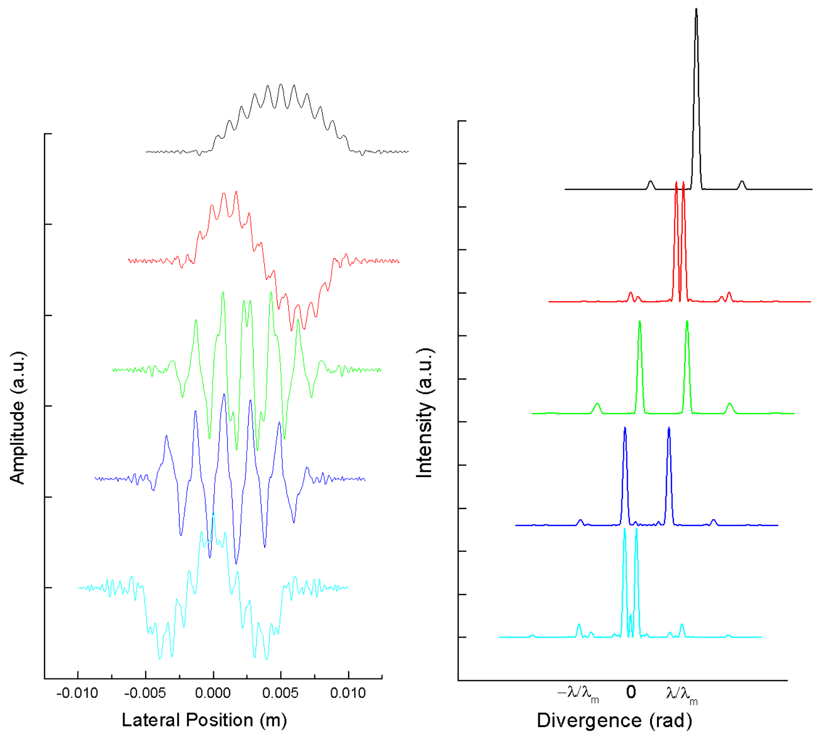

Fig. 3. Left, near-field amplitude profiles of the five lowest-order modes at $d = \pi/8$, $L = 0.625$ m. Right, corresponding far-field intensity patterns.

The near-field amplitude profiles of the five lowest-order modes at $d = \pi/8$, $L = 0.625$ m and corresponding far-field patterns are shown in Fig. 3. First, second, and fifth modes have profiles similar to those of the first, second, and third modes of the corresponding empty cavity. Third and fourth modes are two out-of-phase array modes with beams operating mainly at the position of maximum and minimum of cosine phase modulation, respectively.

It is worth noting that those results are consistent with what one can expect from the combined features of laser arrays and conventional cavities. It seems that generation of array-like coherent output is possible.

Round-trip losses of the three lowest-order modes for different cavity lengths and phase-modulation depths are presented in Fig. 4. The mode order is sorted in increasing order of losses. It shows a highly complex dependence on cavity length. However, it can be seen that, for some values of L, the modal discrimination, which is related to the loss difference between the fundamental mode and the other modes, can be improved compared with a simple plane–plane cavity ($d = 0$). We expect that larger mode discrimination can be obtained by selection of proper phase-modulation function, by use of reflective modulation instead, or by use of combined phase and reflective modulations.

4. Summary

A laterally periodic resonator has been proposed for stabilization and generation of spatially coherent output from large-area gain. Periodicity could be of either phase or amplitude modulation. A periodic resonator laser has the combined features of conventional cavities and laser arrays. The laterally periodic resonator can be considered to be an array of equally separated

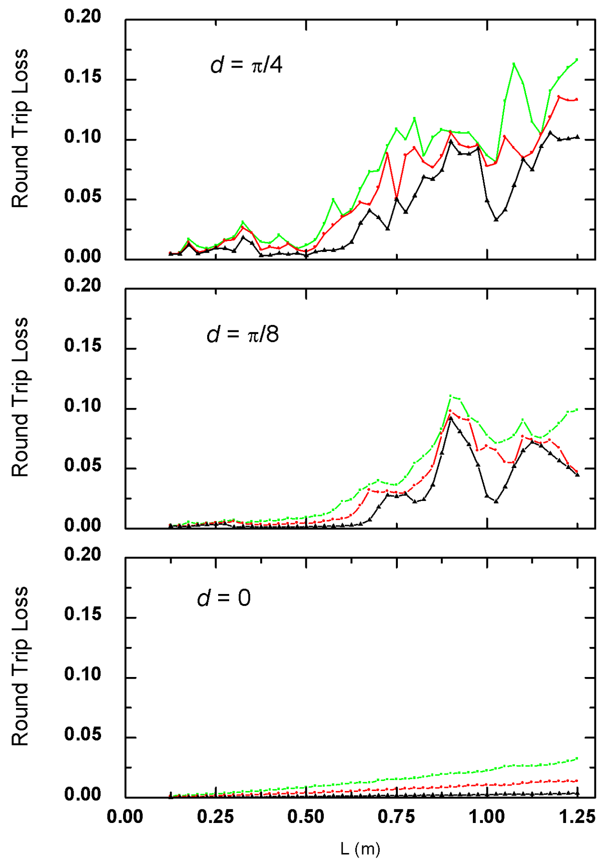

Fig. 4. Round-trip losses of three lowest-order modes for different cavity lengths *L* and phase-modulation depths *d*.

identical subresonators in a "tight binding approximation" when diffractive coupling between oscillations of subresonators is not too strong. Coupled-mode theory can be applied to describe modal structures. And because subresonators have small Fresnel numbers and couple with one another, coherent output from whole laser resonator was found to be possible. When diffractive coupling between subresonators is strong, a more rigorous theory is needed to describe the modal structure. Modal properties of a sample resonator, a plane–plane cavity with an intracavity phase plate of cosine form, were also investigated numerically by an iteration method. Diverse modal structures depending on cavity length and modulation depth were revealed, which have features of both laser arrays and conventional cavities. Modal discrimination of such a resonator was also evaluated and showed strong dependence on cavity length and modulation depth. Thus we expect larger modal discrimination when optimizing the phase-modulation function, by use of reflective modulation instead, or by use of combined phase and reflective modulation. Generation of spatially coherent output from large-area gain by laterally periodic resonators was shown to be possible. More research is needed to develop the concept further.

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