Two-dimensional periodic structures in a nonlinear resonator

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The formation of a periodic transverse structure in the light field in a resonator consisting of mirrors and a thin layer of a nonlinear medium is considered. It is shown that, when the resonator length is a multiple of one half of the Talbot length, there exist periodic structures that are self-imaged under propagation through both the empty part of the resonator and the nonlinear medium. The influence of aperture losses is estimated. It is suggested that this type of a resonator may be useful for diode-array-pumped solid-state lasers.

1. INTRODUCTION

Transverse effects in nonlinear-optical devices are now being widely investigated. Recently experiments have demonstrated synchronization of a laser array by means of the Talbot effect,[1] spatial turbulence and self-organization in a nonlinear-optical system with two-dimensional feedback,[2] and transverse mode locking in a CO_2 laser.[3] The most interesting theoretically, in my opinion, is the development of analytical approaches; their importance can not be overestimated because they provide ways to analyze experimental situations and to test numerical codes.

A wide spectrum of approaches is being discussed. One approach considers the nonlinear coupling of the different transverse modes of an empty resonator (Gauss–Hermite or Gauss–Laguerre modes) and considers the patterns that arise as a result of transverse mode locking.[4,5] Another approach relies on the possibility of solving exactly some envelope equations, by means of inverse scattering transformation within a sufficiently long nonlinear medium, and adjusting their solutions at the boundaries and reflecting surfaces. This method describes the transverse effects in a passive bistable nonlinear interferometer as the formation of the solitary waves of the nonlinear Schrödinger equation.[6]

A third approach reduces the nonlinear diffusion equation that describes a semiconductor bistable interferometer[7] to a kicked dynamics problem. The input laser field is approximated by a set of equidistant δ spikes, so, for one spatial dimension, the integration becomes straightforward and the values of a bistable parameter in nearest-neighbor pixels are connected by a two-dimensional area-preserving map. A fourth approach lies in the approximation of the nonlinear medium as a thin layer, within which the diffraction is negligible. The other part of the resonator is considered to be empty, and the wave field there is transformed by a Fresnel–Kirchhoff integral. As a result, the dynamics of the transverse (and temporal) structure is computed by successively iterating a nonlinear local map (one- or two-dimensional) and a linear nonlocal map (generally speaking, of an infinite number of dimensions).[8] Historically, this method was developed in microwave radiophysics for a traveling-wave tube generator with delayed feedback (see Ref. 9 and references therein). Recently this method has been rediscovered[10] and has been applied to the passive bistable nonlinear interferometer, for which the occurrence of transverse period doublings and switching waves was predicted. A nonlinear resonator with a phase-conjugate mirror also has been modeled by this method.[11]

In Ref. 12 it was assumed that a wide-aperture (large Fresnel number), active optical resonator with a thin active element and nonlinear losses (due to generation of optical harmonics or stimulated light scattering) could be approximately described by a one-dimensional map. This provides a possibility of observing period-doubling behavior, which results in the formation of regular and chaotic transverse structures. It was assumed that such a description is valid only if the effective Fresnel number $ka^2/2\pi nL_R$ is sufficiently high [k is the wave number, L_R is the resonator length, n is the number of passes through the resonator (iterates of the map), a is the effective size of the transverse inhomogeneity of the wave field]. Fortunately, this restriction is not necessary for periodic transverse structures. Our goal is to show that when the resonator length is a multiple of one half of the Talbot length, the phenomenon of self-imaging of the periodic fields will still take place in the presence of a thin layer of an arbitrary nonlinear medium. The paper is organized as follows: In Section 2 the essential features of self-imaging are described, an exact expression for Talbot beam diffraction at a finite aperture is obtained, and its propagation through the thin nonlinear slice is considered. In Section 3 the problem of the efficiency of diode-array-pumped lasers is briefly discussed, and afterward a Talbot cavity with a thin nonlinear amplifying slice inside is proposed. In Section 4 the results are summarized.

2. TALBOT RESONATORS WITH A THIN NONLINEAR LAYER

In 1836 Talbot[13] viewed with a magnifying lens white light passing through an equidistant grating made by Fraunhofer. Talbot was intrigued by the fact that, when the focus of the lens was shifted gradually away from the grating, distinct color bands arose parallel to the lines of the grating. For a

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Окулову А.Ю.

ПРЕЗИДИУМ АКАДЕМИИ НАУК СССР

ПОСТАНОВЛЕНИЕ

28 декабря 1990 г. № 1335

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ФИАН СССР
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О результатах конкурса-экспертизы 1989 года научных проектов и предложений молодых ученых АН СССР по проведению фундаментальных и прикладных исследований, разработке новых методик, материалов и технологий /представление Комиссии АН СССР по работе с молодежью и экспертных комиссий Президиума АН СССР/

В соответствии с постановлением Президиума АН СССР от 24 декабря 1986 г. № 1476 "О дальнейшем совершенствовании работы с молодежью в Академии наук СССР и развитии системы экономического стимулирования научных учреждений АН СССР в осуществлении этой деятельности" в Академии наук СССР в 1989-1990 годах подведены итоги очередного конкурса-экспертизы научных проектов и предложений молодых ученых АН СССР.

Проводимые в рамках реализации экономической программы работы с научной молодежью ежегодные конкурсы-экспертизы являются эффективным механизмом целевого тематического финансирования наиболее важных фундаментальных и прикладных исследований академической молодежи. Конкурсы способствовали осуществлению ряда важных научных проектов, профессиональному и должностному росту многих молодых ученых АН СССР.

Постановлением Президиума АН СССР от 14 ноября 1989 г. № 902 "О плане финансирования научно-исследовательских работ Акаде-

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I	2	3	4	5	6	7
64.	Сверхбыстродействующие кремниевые приборы на основе туннельной генерации носителей, порождающих лавинный ток в p-n переходе (Зубрилов А.С.)	Физико-технический институт им. А.Ф.Иоффе АН СССР				
	Дополнительный фонд оплаты труда		23,0	23,0	23,0	69,0
	Дополнительная численность		4			4
	Дополнительное финансирование на развитие материально-технической базы		76,0	76,0	76,0	228,0
	Командировочные расходы		I,0	I,0	I,0	3,0
		Итого:	I00,0-	I00,0	I00,0	300,0
65.	Разработка резонаторов для твердотельных лазеров с полупроводниковой оптической накачкой (Окулов А.Ю.)	Физический институт им. П.Н.Лебедева АН СССР				
	Дополнительный фонд оплаты труда		8,5	8,5	8,5	25,5
	Дополнительная численность		I			I
	Дополнительное финансирование на развитие материально-технической базы		4I,0	4I,0	4I,0	I23,0
	Командировочные расходы		0,5	0,5	0,5	I,5
		Итого:	50,0	50,0	50,0	I50,0

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Laser-Diode-Pumped Phase-Locked Nd:YAG Laser Arrays

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Abstract—**Scaling of an efficient and compact diode-end-pumped Nd:YAG laser was demonstrated by two-dimensional phase-locked arrays. The arrays of stable resonators were formed by multiple thermal lenses induced by the simultaneous end-pumping of laser-diode-coupled fibers. Because of partial overlap of each transverse mode, the output was phase locked. Various configurations of pumping fibers were tested to study phase locking. It was found that minimization of the coherently coupled intensity between adjacent array elements gave good prediction for phase difference between modes. When the plane parallel cavity as long as 30 mm was pumped by 2 × 2 laser diode coupled fibers, phase-locked 1.8 W continuous wave 1.06 μm output was obtained with 55% slope efficiency. 1.2 W single longitudinal mode output with single lobe beam profile was obtained by using a spatial phase filter and the twisted mode method.**

I. INTRODUCTION

LASER-DIODE (LD) end pumping of a solid-state laser provides excellent efficiency due to the superior spectral and spatial overlap of the pump beam and the resonator mode. Various higher power end-pumped laser systems including multifacet pumping [1], [2], LD multiplexing [3], [4], and fiber-bundle pumping [5]–[7] have been successfully reported. However, further scaleup of end pumping would not only require to increase the dimension of the cavity to support larger fundamental mode, but also loss in efficiency due to the thermal birefringence or aberration. We indicated that diffraction loss increases quadratically with pump power when Nd:YAG was end pumped with tight mode matching between the pump beam and resonator mode [8], [9].

Of course, one of the solutions for scaling is the selection of gain media which is less susceptible to thermal effect. Baer demonstrated better performance in a Nd:YLF because of a smaller coefficient of refractive index change [2]. Another solution for scaling is the coherent addition of individual lasers while keeping maximum efficiency for each laser. Longitudinal coherent addition was demonstrated by a nonplaner ring laser by carefully adjusting each laser frequency [10]. Phase-locked laser arrays are a form of coherent addition. Two-dimensional surface-emitting laser diode arrays with phase-locked output were demonstrated [11], [12]. We proposed and demonstrated, for the first time to our knowledge, novel 2-D arrays for scaling up the efficient end-pumped Nd:YAG laser [13].

Nd:YAG laser arrays were formed by multiple thermal lenses in a plane parallel resonator realized by simultaneous end pumping of laser-diode-coupled fibers. Advantages of the arrays are as follows. The arrays are scalable while maintaining the best efficiency of end pumping, the cavity setup remains compact as a single laser which could be of the order of a few centimeters or less, simple plane parallel optical components can be used, and finally, the arrays are automatically phase locked through the spatial overlap of adjacent modes.

In this paper, the principle of Nd:YAG laser arrays, the mechanism of phase locking through various configurations of pump beams, and the technique to obtain single longitudinal modes with a single spatial lobe are discussed.

II. Nd:YAG LASER ARRAYS

In this section, we describe the setup, efficiency, and scalability of Nd:YAG laser arrays. First the experimental setup shown in Fig. 1 for generating arrays of lasers is explained.

A. Experimental Setup

As a pump source, two 0.9 W broad-area laser diodes (Sony SLD-304XT) [14] with a 200 μm emitting aperture were coupled to a 125 μm core diameter, 140 μm clad diameter, 0.35 NA step index fiber after an anamorphic prism circularizer and polarization multiplexing [6]–[8]. Typically, 1.2 W of pump power on a Nd:YAG rod was obtained per fiber resulting in $\sim$66% efficiency from LD to the Nd:YAG rod. Four fiber-coupled LD modules which contains eight 0.9 W LD's in all were used. Each LD was separately thermoelectrically cooled to tune its wavelength to 808 nm. Approximately 90% of pump beam was absorbed by a 7 mm thick 1.1 at% Nd^{3+} doped YAG rod.

Various configurations of fiber arrays, as shown in Fig. 2, were used to end pump a Nd:YAG rod through coupling optics with the magnification 1.2 and 1.9. Output of the fibers was imaged in the rod to form thermal lenses because of the high power density of the pump, which is approximately 10 kW/cm^2. The 30 mm long cavity consisted of an output flat mirror with 5% transmission at

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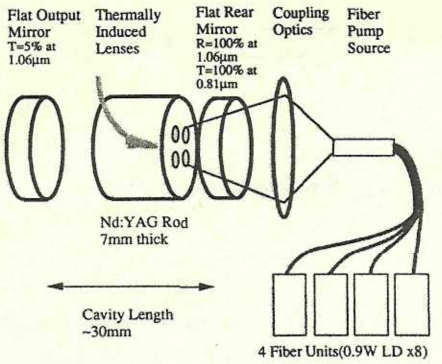

Fig. 1. Schematic of phase-locked Nd:YAG laser arrays.

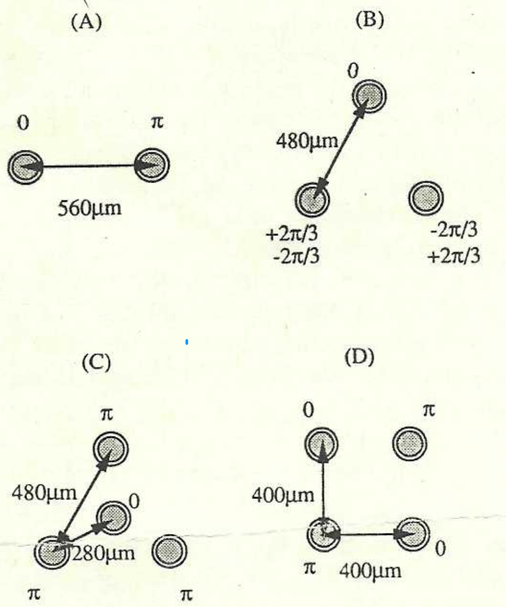

Fig. 2. Various configurations of fibers used to pump the Nd:YAG laser arrays. Shaded areas indicate 125 μm diameter core of the fiber. Phase difference between adjacent modes, which is used to calculate the far field, is shown.

1.06 μm and a flat mirror with 100% reflection at 1.06 μm and nearly 100% transmission at pump wavelength. A plane parallel Nd:YAG rod with antireflection coating at 1.06 μm on both sides was inserted in the cavity.

B. Thermal Lens Cavity

The thermal lens of the end-pumped Nd:YAG laser was analyzed in [7]–[9] and [15]. According to [15], focal length assuming a collimated Gaussian pump beam was given. However, the assumption is not the case for our laser, because of larger divergence and top-hat-like intensity profile of the fiber output. The thermal focusing in our case was numerically evaluated by the finite element method, assuming the heat source was generated by the quantum defect, which is the difference between the pump wavelength and the oscillating wavelength [7]. 1.2 W of pump power should introduce the thermal focal length of 0.91 m when the magnification of the coupling optics is 1.9. The formation of thermal lenses was confirmed both by an interferometric measurement and by observing the mode profile of a single fiber pumped laser. The observed focal length was found to coincide with the calculated value.

Using the calculated focal length, the TEM_{00} mode radius of a 30 mm cavity can be estimated as 230 μm, which perfectly matches our pump size. Coupling efficiency from the pump beam to TEM_{00} mode was analyzed by [16]. The efficiency was evaluated numerically considering the actual divergence of the fiber. It was found that more than 90% of the pump power was coupled to the TEM_{00} mode. The results suggest that a highly efficient end-pumping laser can be realized with a compact cavity.

C. Experiment

As the result of efficient pump beam coupling, the slope efficiency as high as 57% was obtained, when the cavity was pumped by a single fiber with the magnification of 1.9, as shown in Fig. 2. Typically 0.45 W was obtained by a single fiber pumping. The output beam profile was a perfect Gaussian. A thermal lens with a 0.9 m focal length should be induced according to the observed beam divergence of 1.5 mrad, which agreed well with predicted value. It was found there was no decrease of output power with the insertion of a Brewster plate. These results suggest that the effects of thermal aberration and thermal birefringence were negligible at that pump level. Scaling the laser can be expected without losing efficiency and without expanding cavity size. In order to confirm the scaling, four fibers were used to pump the laser. The fibers were located on the corners of a square of 400 μm side as shown in Fig. 2(d). Fig. 3 shows the measured output power characteristics of the laser arrays pumped by 4 fibers. At 4.8 W pump power on rod, 1.8 W output at 1.06 μm with a 55% slope efficiency was obtained. It should be noted that the slope efficiency was close to the case of the single fiber pumping. The far-field pattern exhibited a TEM_{11}-mode-like phase-locked mode, which will be described in the next section.

III. PHASE-LOCKED OUTPUT

Coherent scaling of a laser is desirable to obtain higher brightness. In the case of laser arrays, phase locking between adjacent modes enables coherent scaling. It was found that the phase of arrays can be locked automatically through partial spatial mode coupling. Various configurations of the pump source were tested to study phase relation of the modes [Fig. 2(a)–(d)]. Minimization of the coupled mode intensity was found to predict the phase difference between modes.

A. Two Mode Coupling

The phase relation between adjacent modes was normally antiphase, as was often seen in semiconductor laser arrays. Antiphase relation between adjacent modes for a free-space laser can be intuitively understood by intensity