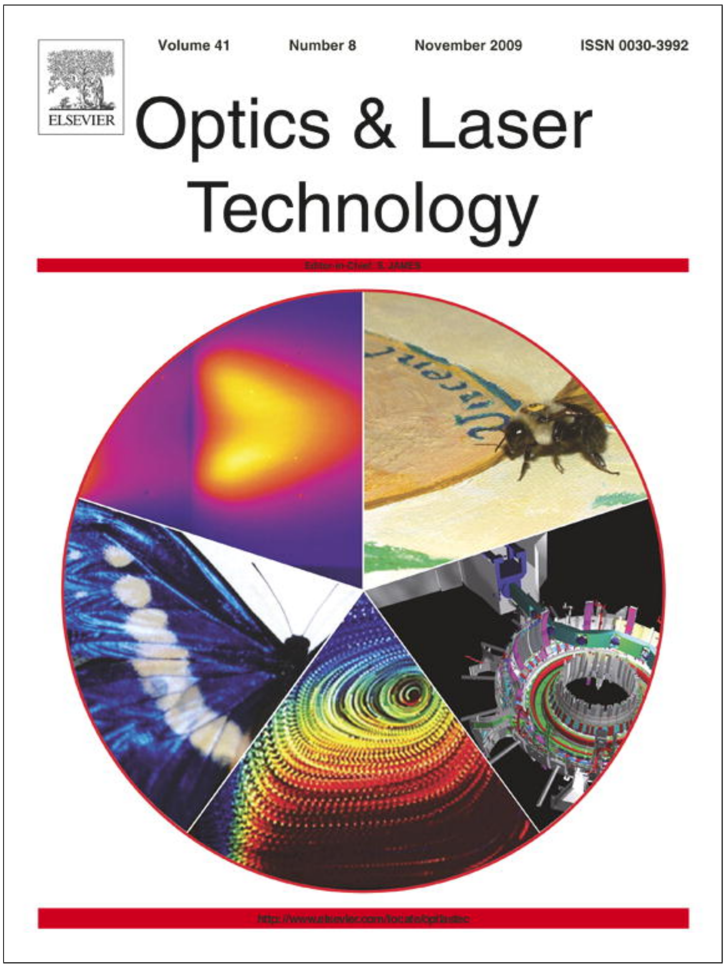
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Operation of pulsed dye laser with an intracavity phase step

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Effects of an intracavity phase step on the spectral and spatial characteristics of pulsed dye laser radiation are studied. In the broadband operation regime of the dye laser, the lasing spectrum was strongly, periodically modulated. In the narrowband regime, periodic alteration between TEM_{00} and TEM_{01}-like beam profiles is observed on tuning the laser wavelength. Two different spectral periods of these effects are recognized. The shorter period corresponds to double passage and the longer one to apparent single passage of intracavity light through the phase step on a cavity round trip. Depending on the position of the phase step along the laser cavity, single-passage period, double-passage period, or a superposition of both periods appeared in the broadband emission spectrum and in the beam profile alteration sequence. These observations demonstrate several possibilities for the control of spectral, spatial, and phase characteristics of laser beams by simple intracavity phase elements.

1. Introduction

A laser medium with a broad gain spectrum can be used to produce either broadband emission or tunable narrowband emission depending on the cavity arrangement. The broadband lasing arises when no spectrally selective elements are present in the cavity. With a selective intracavity element like Fabry–Pérot etalon, controlled multi-wavelength lasing can be obtained as was demonstrated, for instance, for fiber lasers [1]. However, periodic modulation in the lasing spectrum of broadband dye lasers has been observed even without intentional use of any selective element [2–4]. Dasgupta et al. [4] studied this effect in more detail using a pulsed dye laser. They found that strong periodic modulation arises as a result of interference between two parts of intracavity beam, where one part of the beam passes through the dye solution and the other part passes through the wall of the dye cell. If the beam of narrowband dye laser was directed along such solution–wall interface of a standalone cell, a distinct dark patch appeared in the far-field beam profile at certain wavelengths [4].

Here, we report an experimental study of intracavity phase-step effects, but with more advanced control of spectral, spatial, and phase characteristics of the laser emission than was used in [4]. The key element of this study was a thin plate of transparent material inserted into the laser cavity, so that it covered nearly half of the intracavity laser beam. With this arrangement, an intracavity phase step was formed. The plate could be placed in any desired location within the cavity, where other optical elements do not pose an obstacle. Effects of the phase step on lasing characteristics were examined in the two different operation regimes of the dye laser: the broadband lasing when the feedback was provided by a plain total end-reflector, and the narrowband tunable lasing when spectrally selective feedback from a diffraction grating was used.

2. Experimental

The optical scheme of the dye laser under investigation is shown in Fig. 1. The laser cavity had an autocollimative design with a Littrow-mounted grating, as presented in the paper of Hänsch [5]. A 20-mm-long dye cell was pumped by the beam of a XeCl excimer laser through a cylindrical lens. The intracavity dye laser beam was expanded by a four-prism beam expander with the magnification factor of 40 and directed onto a 600-lines/mm blazed grating. A fused silica plate with anti-reflection coating on the exit surface served as the output coupler. An ethanol solution of Coumarin-120 dye was used as the laser medium. Under 5 mJ pumping, the light pulses of about 10 ns duration and 150–170 μJ energy were produced at a repetition rate of 5 Hz. The height and the depth of the pumped region were about 0.5 mm and the cavity length l was about 25 cm. The corresponding Fresnel number $a^2/\lambda l$, where a is the beam radius, was close to, but less than unity. This ensured that the lasing occurred at the lowest order transverse mode TEM_{00}. The bandwidth of the laser line was monitored using a Fabry–Pérot interferometer. The measured profile was about 10 pm FWHM and about 25 longitudinal cavity modes were active within this envelope.

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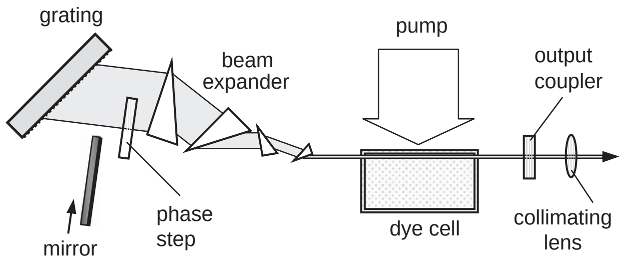

Fig. 1. Schematic view of the dye laser cavity with a phase step. For broadband lasing a plane mirror was inserted to block the grating.

The laser was switched to a broadband operation regime with the aid of a plane aluminum-coated back mirror inserted into the cavity, as shown in Fig. 1. The laser emission spectrum in this case was measured by CCD spectrometer HR-4000 (Ocean Optics) with spectral resolution of 0.15 nm FWHM. Far-field beam profiles were recorded by Silicon Video 9M001M 10 bit CCD camera.

3. Results and discussion

Under broadband operation, the laser emission spectrum consisted of a smooth structureless 8.5-nm-wide (FWHM) band centered near 440 nm (the bottom trace of Fig. 2). The other four spectra in Fig. 2 were measured with various phase plates (microscope cover slip, transparent plastic film, or thin mica sheet) inserted into the cavity to form a phase step. When the phase step was inserted, strong periodic modulation appeared in the spectrum. As expected, the modulation period depends on the thickness and the refraction index of the used phase step. All the modulated spectra in Fig. 2 were recorded with the phase step located near the back mirror, as shown in Fig. 1. In this location, the expanded intracavity beam was about 20 mm wide and the modulated structure of lasing spectra was very stable and tolerant against the transverse shifting of the step. The modulation depth gradually diminished and disappeared, when the phase step was shifted more than ± 5 mm off the beam center. In all cases, the laser pulse energy was insensitive to the position of the step within the cross-section of the beam.

When a monochromatic plane wave with wavelength λ encounters an ideal phase step *i.e.*, a semi-infinite layer of non-absorbing and non-reflecting material with thickness d and refraction index n, the part of the wavefront that passes the layer is retarded by optical path difference $d(n-1)$. When the retardance is equal to a multiple of λ, the transmitted wavefronts are in phase and, if the distortions at step edge are neglected, the wave remains unaffected by the phase step. In general, the retarded part of the wavefront that passed the layer and the part of the wavefront that propagated off the layer interfere. If the retardance is equal to an odd multiple of $\lambda/2$, the transmitted wavefronts have opposite phases and a symmetric dark region of destructive interference is formed behind the step edge [6–10]. On changing the wavelength, the same interference pattern reappears periodically. The recurrence period $\Delta\lambda$ is given by

$$\Delta\lambda = \lambda^2/[d(n-1)] \quad (1)$$

Fig. 3 shows the captured far-field beam intensity profiles for the dye laser operated with the intracavity phase step in the narrowband lasing regime. On tuning the laser wavelength, a gradual periodic transformation between slightly elliptical gaussian-like profile, shown in the top panel of Fig. 3, and a profile with clearly visible dark region, shown in the bottom panel of Fig. 3, occurred. The beam profile alteration period was directly readable from the wavelength counter and, for a given phase step, this period matched with the modulation period of the corresponding broadband emission spectrum. The light intensity in the dark region of beam profile was at its minimum at wavelengths which corresponded to the minima in modulated broadband spectra of Fig. 2. This indicates that both effects have the same origin, i.e., they result from the destructive interference of two oppositely phased intracavity sub-beams. The appearance of a minimum in the beam profile, however, was not accompanied by a decline in the total laser pulse energy and there was no wavelength-dependent intensity modulations, like in the case of broadband operation. Thus, the energy of laser pulse is redistributed periodically from the TEM_{00} profile to a TEM_{01}-like one and back when the laser wavelength is tuned. The presence of a phase step in the laser cavity did not result in a measurable change of the laser line width.

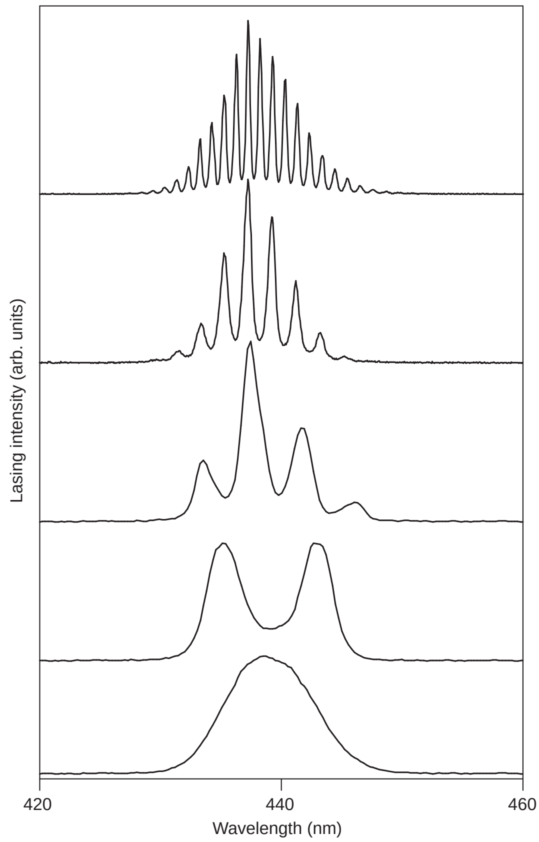

Fig. 2. Broadband emission spectra of the dye laser operated without a phase step (bottom trace) and with different phase steps (upper traces).

Fig. 4 demonstrates the transformation of broadband lasing spectrum for different positions of the phase step along the laser cavity. For a given phase step, the characteristic spectral period $\Delta\lambda$ in Eq. (1) was determined from the interference pattern alteration measurement, in case the step was placed into the output beam of the narrowband dye laser. When the same phase step was inserted into the laser cavity as shown in Fig. 1, the spectral period (Fig. 4, upper trace) was always two times shorter than the characteristic period $\Delta\lambda$. A twice larger path difference for the intracavity phase-step results from a double passage of intracavity light through the step during each cavity round trip, which comprises a forward passage towards the end of the cavity and a return passage after reflection from the end mirror or grating. This double-passage period, given by $\lambda^2/[2d(n-1)]$, persisted also if the step was placed anywhere between the prisms of the beam expander.

However, if the step was inserted between the expander and the dye cell, i.e., close to the cavity center, the interference period

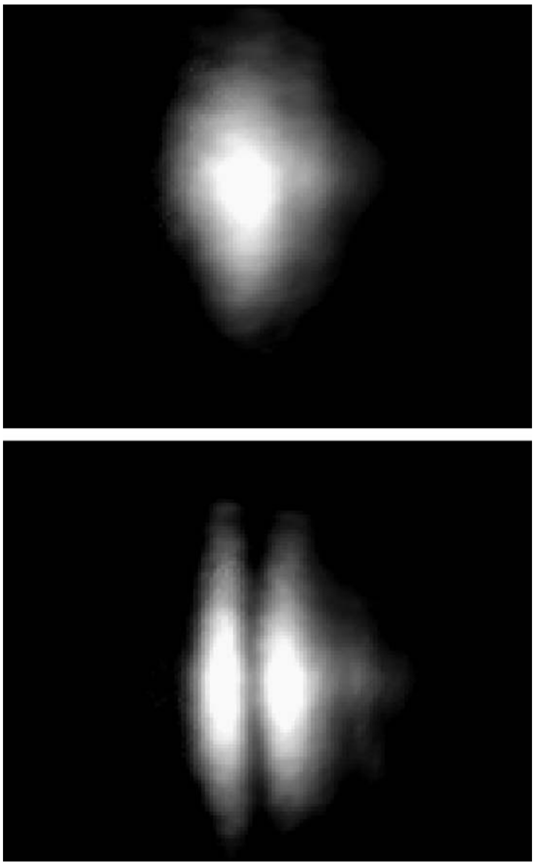

Fig. 3. Far-field beam profiles of the narrowband dye laser operated with an intracavity phase step: top—regular TEM_{00} mode; bottom—TEM_{01}-like mode.

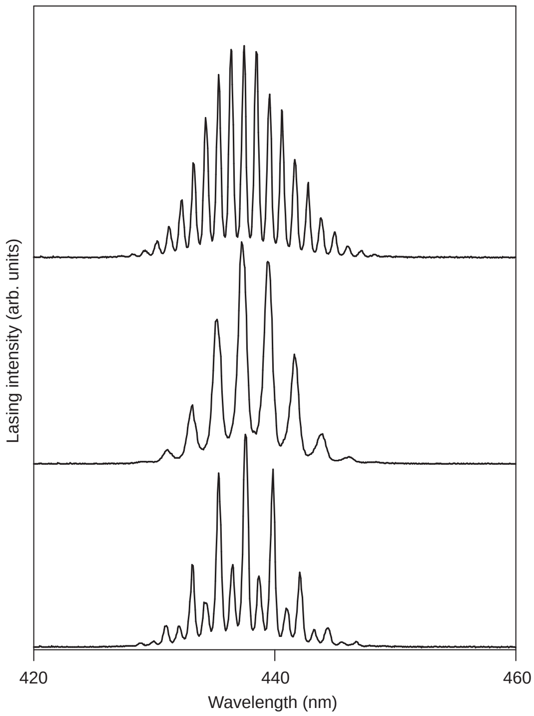

Fig. 4. Broadband emission spectra for three different locations of the phase step: top - double-pass spectral modulation when the step is near the back mirror; middle - single-pass modulation when the step is near the cavity center; bottom - mixed modulation when the step is near the output coupler.

was increased by a factor of two (see the middle trace in Fig. 4) and became equal to a single-pass interference period $\Delta\lambda$ measured for the step placed into the outgoing laser beam. Hence, the phase step located near the cavity center gives rise to the spectral modulation that corresponds to apparent *single* passage of the intracavity light through the step on a cavity round trip. This observation is in agreement with the single-pass period of spectral oscillations reported by Dasgupta et al. [4], where the phase step formed by the dye solution and the wall of the dye cell was located just in the middle of the cavity.

When the phase step was moved towards the output coupler, a more complex pattern of mixed spectral modulations appeared, where both single- and double-pass periods were superimposed (Fig. 4, bottom trace). The relative contribution of each particular period was very sensitive to alignment of optical elements, so that either single- or double-pass period could be made dominating. Similar position-dependent interplay of single- and double-pass periods was observed also if the phase step was inserted vertically into the intracavity laser beam.

Besides the well-pronounced single- and double-pass periodic modulation, weak ripples on the spectral peaks sometimes appeared. This additional modulation is attributed to the Fabry–Pérot etalon effect arising from the reflecting surfaces of the intracavity phase step. For a given plate, the period of etalon modulation, $\lambda^2/(2dn)$, is $n/(n-1)$ times shorter than the period of double-pass phase-step modulation, $\lambda^2/[2d(n-1)]$. The etalon effect was observed with very high contrast when the output coupler of the laser was replaced with a cover slip. In this case, a deep modulation in the lasing spectrum results from fully modulated wavelength-dependent feedback from the reflecting etalon.

It is instructive to compare our method with the well-established method for selecting a desired cavity mode by an intracavity binary phase element in fixed-wavelength lasers [11–13]. The simplest binary phase element is a phase step designed to have π-valued phase retardance at the laser wavelength. When such step is placed close to the output coupler or to the back mirror, no effect on cavity modes is expected because of 2π double-pass phase difference on a round trip. However, all the cavity modes except for the TEM_{01} mode encounter distortion caused by a sharp phase change at their intensity maxima, and are suppressed due to increased losses [11–13]. This kind of selection of the TEM_{01} or a higher cavity mode has been demonstrated for moderate-gain YAG and CO_2 lasers, where the cavity Fresnel number was >1 [11,12]. On the contrary, in our case of high-gain pulsed dye laser, the phase step had no effect on regular TEM_{00} lasing at wavelengths, at which the double-pass phase retardance was an integer multiple of 2π. Laser pulse energy was not decreased and the output beam acquired a TEM_{01}-like profile at wavelengths, at which the step flips the phase of the wavefront to the opposite one. We suppose that the formation of new kind of transverse cavity modes rather than the selection of modes that exist without a phase step, takes then place. Numerical modeling of these effects is underway.

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