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为进一步办好《光学学报》而努力

中国光学学会副理事长
《光学学报》主编
王之江

《光学学报》自一九八一年创刊以来，积极反映我国光学领域中科研发展的新成就，促进了学术交流，并从双月刊改为月刊，受到了国内外光学界的欢迎。

在此，首先让我代表编委和编辑部，向创办了《光学学报》并亲自任第一任主编的王大珩教授，致以崇高的敬意。《光学学报》从无到有，进而达到国内外公认的学术和出版水平，这与他的悉心领导是分不开的。在前不久召开的光学学会第二届理事会上，他因年高坚持辞去主编之职。我们坚信，作为光学学会理事长，他必将一如既往地领导和关注学报的工作，给予我们必不可少的支持。

同时，让我向第一届编委和编辑部，向广大作者、审稿者、读者及所有支持学报工作的单位和个人表示感谢。

现在，第二届主编已由光学学会第二届理事会任命，第二届编委也已由主编聘任。

为适应国家经济、科技改革的新形势，加快传递和交流光学界学术信息，尤其为使一些首创性的科研成果能尽快公诸于世，从1985年起本刊决定增设快报栏。

为了集中地反映若干学科分支的科研成果，我们打算出一些专辑，欢迎广大专家、作者推荐专题和投稿。

为了促进国际性学术交流，本刊要求来稿的英文提要增加到500字左右。

此外，为了活跃学术气氛，希望广大读者对本刊已发表的文章展开讨论。我们将以读者来信的形式摘要刊登讨论意见。

最后，欢迎广大作者和读者对本刊提出批评和建议，欢迎大家踊跃投稿和订阅，为进一步办好本刊而努力。

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Operating Characteristics of a Colliding Pulse Mode-Locked Ring Dye Laser

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Abstract

The operating characteristics of a colliding pulse mode-locked ring dye laser using DODCI and DQOCI dye as saturable absorbers are studied. Measurement results of the dependence of the pulse width of the mode-locked pulses, the stability range of laser for stationary single-pulse operation and the threshold pumping power on the concentration of the absorber dye are given. Stable pulses with duration of 0.12 psec and peak power of 1kW can routinely be obtained with this laser at a low pumping power (about 2W). The results of the spectrum-resolved SHG correlation measurements of the mode-locked pulses also are presented, which confirmed the presence of frequency chirping in the pulses. It has been found that by using DQOCI dye as the saturable absorber the spectrum of the laser output consists of two separate parts located in the yellow and red regions respectively, and when the oscillation in yellow is supressed the modelocking stability is improved and the output pulses exhibit clean pulse shapes with much reduced wings.

1. Introduction

Since Fork et al[1] reported the generation of stable 90-fsec pulses by means of the technique of colliding pulse modelocking (CPM) in a cw pumped passively mode-locked ring dye laser, the CPM technique has been widely applied in generating ultrashort optical pulses with duration shorter than 100 fsec. It was reported that 55-fsec pulses were obtained directly in a CPM ring dye laser[2] and 30-fsec pulses were produced by using optical pulse compression techniques in an oscillator-amplifier system[3]. Some other experimental and theoretical results on CPM ring dye lasers were also reported[4~8].

We have experimentally studied the operating characteristics of a CPM ring rhodamine 6G (Rh-6G) dye laser, which is pumped with a cw argon ion laser and uses DODCI or DQOCI dye as the saturable absorber. In this paper we present some experimental results on our CPM ring dye laser, including the dependence of CPM pulse width, the stability range of the laser for stationary single-pulse operation and the threshold pumping power on DODCI dye concentration, as well as the results of the spectrum-resolved SHG correlation (SR-SHG) measurement of the optimal CPM pulses. We also present some interesting results when DQOCI dye was used as the saturable absorber.

2. Experimental

The schematic diagram of our CPM ring dye laser is shown in Fig. 1. The solution of rhodamine 6G (2×10^{-3} M in ethylene glycol) is made to flow in a 0.3-mm-thick jet stream placed at the common focus of the folding mirrors of 5-cm focal length and pumped by a cw argon ion laser operating at all lines with a power of about 2 W. The saturable absorber, jet stream of DODCI or DQOCI solution in ethylene glycol, is placed at the common focus of the folding mirrors of 2.5-cm focal length. For DODCI, values of the jet thickness of both 100 μm and 40 μm were tried, while for DQOCI, only 100 μm was used.

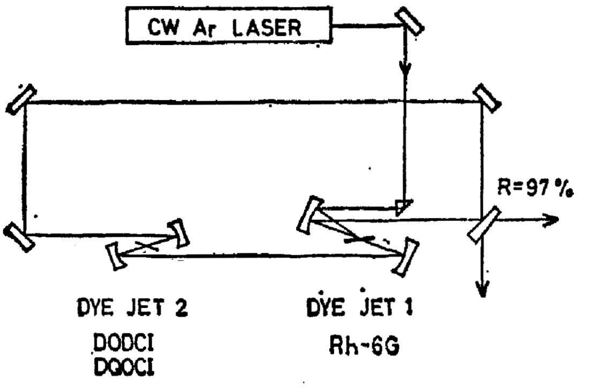

Fig. 1 Schematic diagram of the CPM ring dye laser

The output coupling mirror is 97% reflective in the range of 550~650 nm, while other mirrors are nominally 100% reflective in the same range. The cavity roundtrip time is approximately 10 nsec, and the laser is adjusted such that the distance between the amplifier and absorber jets is one quarter of the roundtrip path-length to equalize pulse amplitudes and to maximize modelocking stability[7].

Figure 2 shows the experimental arrangement. One of the output laser beams is

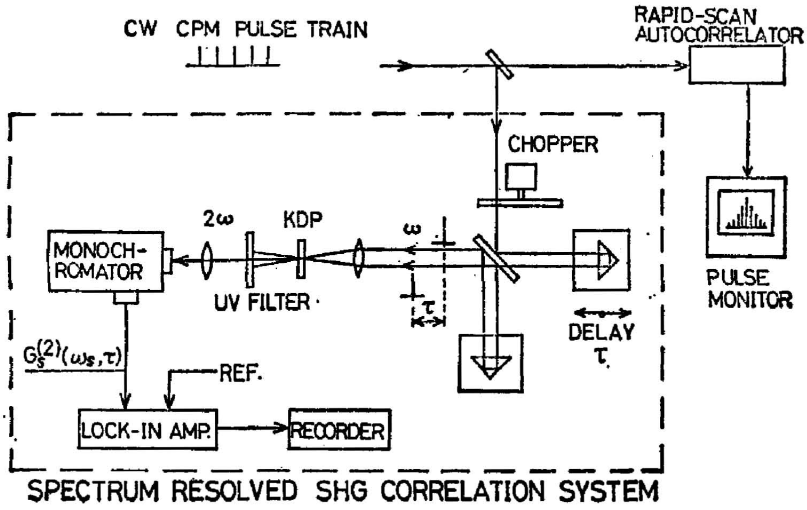

Fig. 2 Experimental arrangement to measure output characteristics of the CPM pulses

directed to a rapid-scan autocorrelator[9] as a continuous monitor of the width and profile of the output pulses to optimize the output performances, and the other is led to an SHG correlation system for carrying out either spectrum-resolved or conventional measurements of SHG autocorrelation of CPM pulses[10]. The harmonic crystal used is a 0.4-mm-thick KDP; the focal length of its focusing lens is 10 cm.

3. Results and discussion

The operating characteristics of the CPM ring dye laser have been experimentally studied by using DODCI or DQOCI dye as a saturable absorber. The threshold pumping power of this laser configuration is lower than 250 mW (without absorber jet).

It was observed that the pulse width of the CPM pulses became short and the pumping power range of the laser for stationary single-pulse operation became broad with increasing DODCI dye concentration for a given jet thickness. The results obtained by using two different jet thicknesses (100 μm and 40 μm) are illustrated in Fig. 3. Figure 3(*a*) shows the pulse widths, deduced from the measured SHG autocorrelation widths of the CPM pulses under the assumption of a sech^2 pulse shape, as a function of DODCI dye concentration for the two jets, respectively. Figure 3(*b*) shows the threshold pumping power curves and the stability regions which lie between upper and lower boundaries denoted by pairs of dashed lines, as functions of DODCI dye concentration for the two jets, respectively. Vertical bars in these regions denote measured values of the possible pumping power ranges for single-pulse operation corresponding to given DODCI dye concentrations; within each range, the measured pulse width changes slightly. The data-point on each bar denotes the pumping power corresponding to the pulse width shown in Fig. 3(*a*).

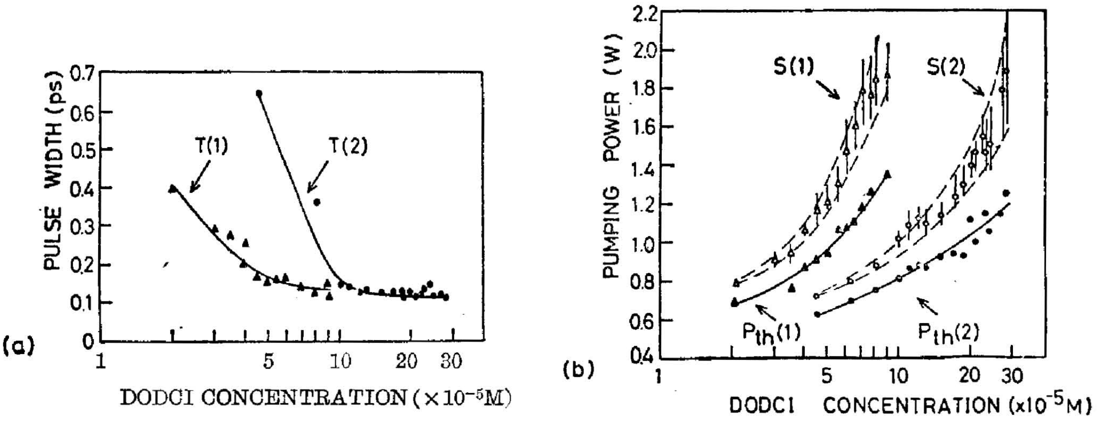

Fig. 3 (*a*) Pulse width T of the CPM pulses as a function of DODCI dye concentration, and (*b*) threshold pumping power P_{th} and stability region S of the laser for stationary single-pulse operation as functions of DODCI dye concentration (1: for 100 μm jet thickness, 2: for 40μm jet thickness)

As shown in Fig. 3, the trend of pulse width shortening tends to saturate when DODCI dye concentration exceeds a certain value for a given jet thickness, but the corresponding possible pumping power range for stationary single-pulse operation still becomes broader with increasing DODCI dye concentration. Pulses as short as 0.12 psec (FWHM) with peak power of 1kW were routinely obtained at a low pumping power level (about 2W) and the shortest pulses (as short as 0.11 psec) were also observed in this laser.

The phenomenon that the pulse width shortening tends to saturate for a given DODCI dye jet thickness can be explained as follows. For a given set of dye laser parameters the combined action of absorber nonlinearity and laser gain saturation can generate ultrashort pulses. In the stable operating regime, when a pulse circulating in the cavity passes through the absorber its leading edge is absorbed more strongly than its peak and trailing edge owing to the saturable absorption. While the pulse passes through the gain medium its trailing edge receives less amplification than its peak, it may even experiences a net loss because of gain saturation. Thus the nonlinear absorber acts to continuously increase the slope of the leading edge of the pulse, on the other hand, the nonlinear amplification also can sharpen the trailing edge of the same pulse. Such actions lead to a rapid compression of the pulse, and the effect becomes more prominent with absorber having higher concentration. However, as the pulse width becomes comparable to the thickness of the absorber jet stream, the pulse compression effect of increasing absorber dye concentration weakens and even tends to saturate because the compression of the pulse balances with the temporal broadening of the pulse by the group velocity dispersion of the resonator (including the dispersion in dye jet streams and in mirror coatings). For the generation of pulses shorter than 100 fsec, even small amounts of dispersion present a problem. For generating shorter pulses the saturable absorber should be sufficiently thin so that the optical path in the absorber is of the order of or shorter than the desired pulse width, and one must develop techniques to decrease or compensate for the inherent dispersion in dielectric mirror coatings and dye solutions. Likewise, pulse compression can be improved by reducing the linear loss in a resonator, adding as much saturable absorber as possible, and focusing more tightly in the saturable absorber.

In fact, for example, Fork et al[3] generated 90-fsec pulses by adopting a special nozzle to produce an absorber dye stream approximately 10 μm thick in a CPM dye laser. They then reduced the pulse width to 65 fsec by varying the mirrors of the resonator.

The spectra of the CPM pulses also were observed under different DODCI dye concentrations. It was found that the spectrum of the laser output became broader and red-shifted gradually with increasing DODCI dye concentration, and the profile of the spectral line exhibited large asymmetry with a broad wing on the long-wavelength side only. Figure 4 shows a typical spectrum and SHG autocorrelation profile of the CPM pulses under the condition of a DODCI dye concentration of 2.8×10^{-4} M and a jet thickness of 40 μm. The time-bandwidth (in frequency) product deduced from these results gives a value of 0.34, which is somewhat larger than the theoretical value of 0.315 for a transform-limited sech^2 pulse.

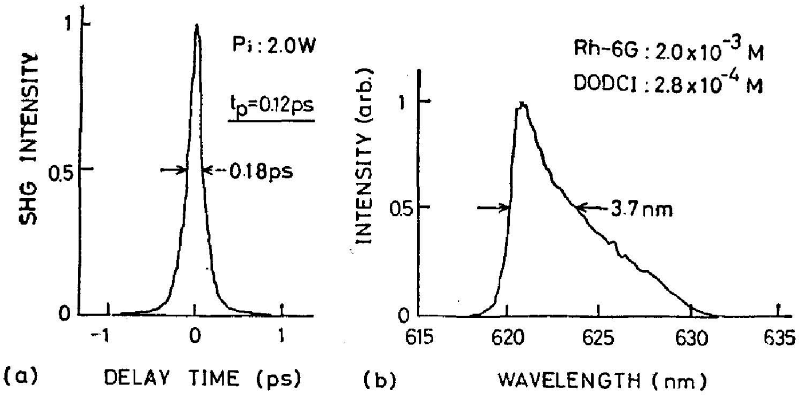

Fig. 4 SHG autocorrelation trace (*a*) and spectrum (*b*) of the CPM pulses at DODCI dye concentration of 1×10^{-4} M and 100 μm jet thickness

This spectral asymmetry is supposed to arise mainly from the asymmetry of phase in time caused by the self-phase modulation. This modulation is produced by passing the pulse through dye solutions which show large intensity dependence of the refractive index due to both the repeated cavity roundtrip and the unexpectedly large nonlinear refractive index n_2 of dense dye solutions in spite of their short length. A more detailed investigation on the spectral characteristics of the CPM pulses is presented in Ref. [11].

In order to get some information on both the shape and the phase characteristics of the CPM pulses, we measured the second harmonic (SH) output by using the spectrum-resolved method[10,12], where the correlation function $G_s^{(2)}(\omega_s, \tau)$ is measured with respect to two variables ω_s (SH frequency) and τ (delay time). The experimental arrangement of the SR-SHG correlation measurement is shown in Fig. 2. The SHG signal obtained from the conventional noncollinear background-free SHG correlator is measured again corresponding to any SH frequency component ω_s by means of the monochromator. If the SR-SHG correlation function $G_s^{(2)}$ $(\omega_s\ \tau)$ is determined as a function of the variable ω_s, we can get the information on both the symmetry of pulse shape and the phase characteristics of the CPM pulses from the fact whether $G_s^{(2)}$ (ω_s, τ) is symmetric with respect to ω_s. For example, if we take the electric field of the fundamental pulses as

$$E(t)=A(t)\cos[\omega t+\phi(t)], \tag{1}$$

the SR-SHG correlation function is given by the expression

$$G_s^{(2)}(\omega_s, \tau) = \left| \int_{-\infty}^{\infty} A(t)A(t+\tau)\exp\{i[\phi(t)+\phi(t+\tau)-\Delta\omega t]\}dt \right|^2 \tag{2}$$

where $\Delta\omega(=\omega_s - 2\omega_0)$ is a fraction of SH frequency deviation, and ω_0 is the central frequency of the fundamental pulses.

From Eq. (2), if both $A(t)$ and $\phi(t)$ are symmetric, i. e.

$$\begin{aligned} A(-t) &= A(t), \\ \phi(-t) &= \phi(t), \end{aligned} \tag{3}$$

we have

$$G_s^{(2)}(-\Delta\omega, \tau) = G_s^{(2)}(\Delta\omega, \tau). \tag{4}$$

On the other hand, if $G_s^{(2)}(\Delta\omega, \tau)$ is asymmetric with respect to $\Delta\omega$, both $A(t)$ and $\phi(t)$ or either of them would certainly be asymmetric. Thus when the SR-SHG correlation function measured is further compared with theoretical curves for various shapes and phase characteristics of the pulses, the information on $A(t)$ and $\phi(t)$ can be obtained.

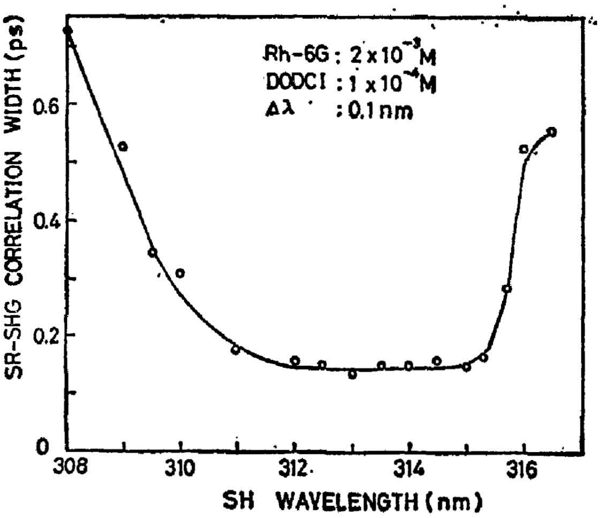

Fig. 5 Spectrum-resolved SHG autocorrelation width as a function of SH wavelength (resolution 0.1 nm)

Figure 5 shows the SR-SHG correlation width $\Delta\tau$ as a function of the SH wavelength (resolution 0.1 nm) for a DODCI dye concentration of 1×10^{-4} M and a jet thickness of 100 μm. It can be seen that $\Delta\tau$ at middle SH wavelength is smaller than at both short and long SH wavelengths. From the asymmetric curve in Fig. 5, we can estimate that the CPM pulses are chirp due to the asymmetry of phase in time caused also by the effect of self-phase modulation as interpreted in some previous and recent papers[10~12].

We have also studied the operating characteristics of our ring dye laser using DQOCI dye as a saturable absorber. The pulse width of the CPM pulses also became shorter with increasing DQOCI dye concentration like the case with DODCI, but the pumping power range for single-pulse operation was very narrow in comparison with that with DODCI. This result can be explained by the following experimental results. We have found that the spectrum of the laser output consists of two separate parts located in yellow and red regions, respectively, as shown in Fig. 6(*a*). The SHG autocorrelation traces of the CPM pulses measured in these spectral parts revealed that in the short wavelength region the pulse width became very broad showing incomplete modelocking, while in the long wavelength region it became short showing good modelocking. When the laser oscillated in these two regions simultaneously, the modelocking became unstable due to competition between the two oscillations, and the SHG autocorrelation profile showed large wings. When the laser was made to operate under the condition of slightly-above-threshold and well-adjusted cavity, the output intensity in the short wavelength region greatly weakened or even vanished. In such case the modelocking stability was improved and the output pulses exhibited clean pulse shapes with greatly reduced wings. These results are shown in Fig. 6(*b*).

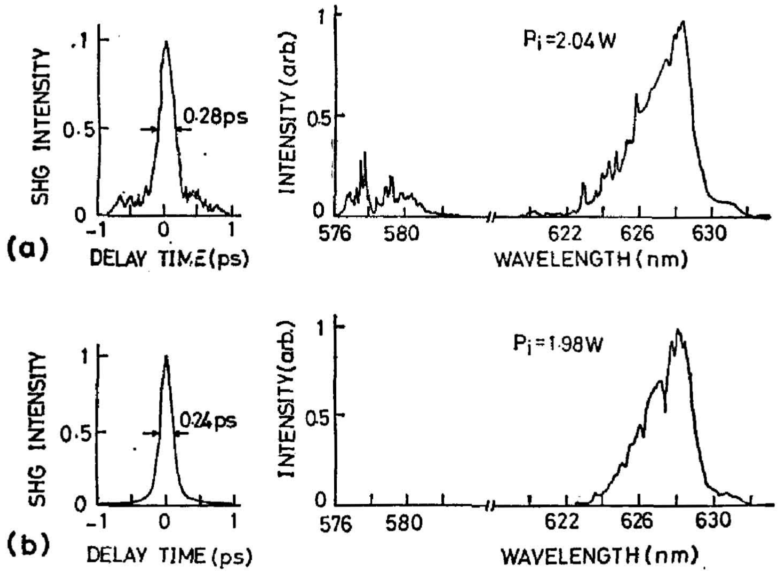

Fig. 6 SHG autocorrelation traces of the CPM pulses(left) and their corresponding spectra (right) under the conditions of Rh-6G dye concentration of 2×10^{-3} M and DQOCI dye concentration of 8.5×10^{-5} M. (*a*) Oscillation in both yellow and red regions, and (*b*) oscillation in red region only. P_i is pumping power

We think that the oscillation behavior in the two spectral regions can be attributed to the formation of new photoisomers in the absorber dye solution, but detailed investigation is yet to be carried out.

No further attempt was made to minimize the pulse width with DQOCI absorber under the present cavity mirror condition, because unwished oscillation in yellow region takes place easily and leads to unstable modelocking. However, it can be expected that if the oscillation in yellow region is fully supressed by some means, such as proper selection of reflective wavelength range of cavity mirror coatings or application of proper additional absorber dye, the pulse width of the CPM pulses will further be shortened and the stability region of the laser will further be broadened.

In summary, we have measured some operating characteristics of the CPM ring rhodamine 6G dye laser using DODCI or DQOCI dye as a saturable absorber. We have routinely obtained stable pulses as short as 0.12 psec using this laser. It has been

shown that when the dye concentration increases, the CPM ring dye laser operates with shorter pulse width, broader stability range and higher output power. The SR-SHG correlation measurements of the CPM pulses confirmed that frequency chirping has occured in the CPM pulses; therefore, the self-phase modulation effect must be taken into consideration in the design and application of CPM ring dye lasers.

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对撞脉冲锁模环形染料激光器的运转特性

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提要

研究了用DODCI和DQOCI染料作为可饱和吸收体的对撞脉冲锁模环形染料激光器的运转特性。提供锁模脉冲宽度、激光器以稳定单脉冲工作的稳定性范围和阈值泵浦功率等，对吸收体染料浓度依赖关系的测试结果。表明了用此激光器，在低的泵浦功率(约2W)下，日常能产生脉宽为0.12ps、峰值功率为1kW的稳定脉冲。给出用光谱分辨的二次谐波自相关法测量输出脉冲的结果，证实在锁模脉冲中已发生频率调制。实验中发现用DQOCI染料作为可饱和吸收体时，激光输出光谱由黄光和红光两个分立部分构成。当黄光的振荡被抑制时，锁模稳定性改善且输出脉冲形状整齐、前后沿包含很小的能量。

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