[1] S. BUFFAGNI and T. M. DUNN, Nature London **188**, 937 [1960]. — F. A. COTTON, D. M. L. GOODGAME, and M. GOODGAME, J. Amer. Chem. Soc. **84**, 167 [1962].
[2] C. FURLANI and A. FURLANI, J. Inorg. Nucl. Chem. **19**, 51 [1961].
[3] S. I. CHAN, B. M. FUNG, and H. LÜTJE, J. Chem. Phys. **47**, 2121 [1967]. — H. LEVANON and Z. LUZ, J. Chem. Phys. **49**, 2031 [1968].
[4] R. POTTEL, Ber. Bunsenges. Phys. Chem. **69**, 363 [1965].
[5] K. KREUTER, Z. Naturforsch. **23 a**, 1728 [1968].
[6] W. LOHMANN, C. F. FOWLER, W. H. PERKINS, and J. L. SANDERS, Nature London **209**, 908 [1966].
[7] F. HUFNAGEL, Z. Naturforsch. **25 a**, 1143 [1970].

Characteristics of a Tunable Travelling Wave Dye Ring Laser

G. MAROWSKY, L. RINGWELSKI, and F. P. SCHÄFER

Max-Planck-Institut für Biophysikalische Chemie
(Abteilung Laser-Physik)
Göttingen, West Germany

(Z. Naturforsch. **27 a**, 711—713 [1972]; received 21 February 1972)

A flashlamp pumped dye ring laser using 4 Abbé prisms of constant 90 degree deviation has been built. Travelling wave operation is obtained when the counterclockwise wave is fed back by a beam-splitting output prism. The laser emission offers remarkable frequency stability when narrowed down to a linewidth of 7 pm by the use of an intracavity solid Fabry-Perot etalon.

Introduction

Various methods are known for the achievement of tunable, narrowband emission from organic dye lasers [1–3]. By inserting frequency selective elements — based on dispersion, rotational dispersion or interferometry — into the cavity, the spectral output can be reduced from some ten nanometers to a fiew picometers. Tunable narrowband laser emission down to a linewidth of 50 pm was reported by SCHÄFER and MÜLLER [4] using a six-prism ring laser. In the present work, we describe the properties of a ring laser using 4 Abbé or Pellin-Broca prisms whose emission was additionally spectrally narrowed by the insertion of a Fabry-Perot etalon into the laser resonator.

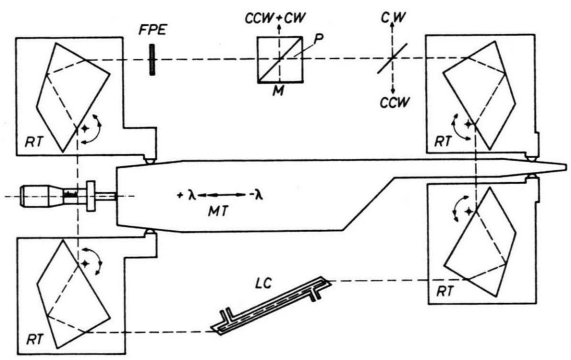

Fig. 1. Ring laser unit; LC: laser cuvette; RT: rotating prism table with Abbé prisms, axis and sense of rotation indicated; MT: movable table; FPE: Fabry-Perot etalon; P: beam splitting output prism with high reflectivity mirror M, for clarity the output prism has been rotated by 90° around the beam axis; G: glass sampling plate for separate measurement of CW and CCW output.

Dye Laser Construction

The flashlamp pumped dye laser consisted of a Brewster angled, 80 mm long, 2 mm internal diameter quartz glass dye cell within an elliptical cylinder reflector. It was optically pumped by a linear flashlamp (pump energy 200 J, ILC dye laser flashlamp type 4D3). The ring-shaped resonator (Fig. 1) was made of 4 highly dispersive (Schott SF 10 glass) Abbé prisms of constant 90° deviation arranged at Brewster's angle to avoid reflection losses. The wavelength tuning was achieved by simultaneous counter rotation of the 4 mechanically coupled prisms. To change the wavelength from 436 m to 656 nm a prism rotation of 2.4° was necessary [5]. One advantage of the arrangement lies in the fact that the lateral displacement of the beam does not exceed 0.1 mm for a 220 nm wavelength interval. In addition, only a single prism set is necessary for tuning throughout the whole visible and near infrared spectral region. The simultaneous counter rotation of the 4 prisms was accomplished by means of the linear motion of a table equipped with roller bearings of high mechanical precisions.

Power was extracted from the ring laser by a dielectric beam splitting prism of 25% reflectivity. Three faces of this prism were antireflection coated whereas the fourth face was provided with a high reflectivity coating. The latter served to increase the output and to force the laser into unidirectional, travelling wave operation, by partially reflecting the counterclockwise (CCW) wave back onto itself [6]. For further spectral narrowing of the laser emission an intracavity solid Fabry-Perot etalon (FPE) was employed. It consisted of a multilayer coated quartz plate of 0.25 mm thickness with a free spectral range of about 0.58 nm at 660 nm (further details cf. [7]) * and had a reflectivity of 78%. By tilting the FPE around a horizontal axis, the emision wavelength could be shifted by a few picometers.

Results

Figure 2 shows the peak output power obtained from various dyes within the wavelength range 550 nm to

* The Fabry-Perot etalon was kindly put at our disposal by Dr. W. SCHMIDT, Carl Zeiss, Oberkochen.

650 nm. The data were taken at a constant pump energy of 200 J (1 μF, 20 kV) ** and with travelling wave operation of the laser. A far field photograph of the output showed a beam divergence of 1.2 mrad (full

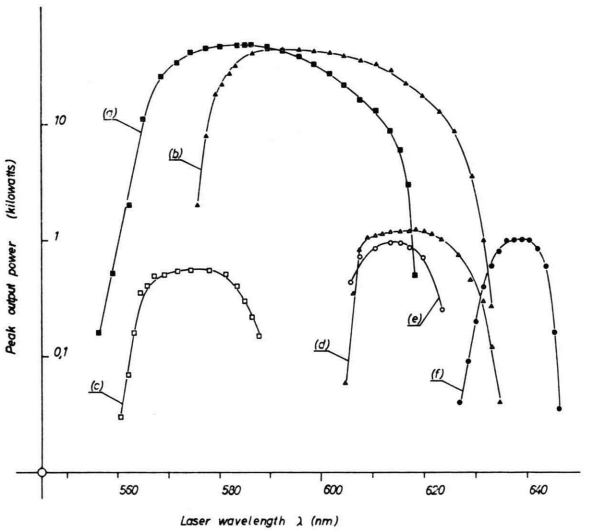

Fig. 2. Tuning range and peak output power for different dye solutions at constant pump energy of 200 J; (a) rhodamine 6G, $2 \cdot 10^{-4}$ molar in methanol; (b) rhodamine 6G, $2 \cdot 10^{-4}$ molar in water with cyclooctatetraene ($2 \cdot 10^{-4}$ molar) and Ammonyx^{R} (2.5%) added; (c) 6-acetylaminopyrene-1,3,8-trisulfonate, $2 \cdot 10^{4}$ molar in water; (d) sulforhodamine B, $3 \cdot 10^{-4}$ molar in methanol; (e) rhodamine B, $3 \cdot 10^{-4}$ molar in methanol; (f) rhodamine 6G, $7 \cdot 10^{-4}$ molar and cresyl violet, $8 \cdot 10^{-5}$ molar in methanol, according to (8).

angle at half-maximum intensity). The total pulse duration varied from 75 nsec (6-acetylaminopyrene-1,3,8-trisulfonate) to 1 μsec for rhodamine 6G. Insertion of the FPE reduced the spectral halfwidth of the emission from less than 1 nm to 7 pm. In contrast to the modal behavior of linear cavities, spectral analysis with an external interferometer revealed no marked or reproducible modal structure. The linewidth obtained by using the intracavity FPE was only weakly affected by variations of the pump energy. Using a $2 \cdot 10^{-4}$ molar solution of rhodamine 6G in methanol, the linewidth increased from 7 pm to 8 pm as the pump energy was raised from 22 J near threshold to 200 J.

The absence of a modal structure evidently contributed to the remarkable wavelength stability from shot to shot. The coarse adjustment by simultaneous prism rotation allowed a reproducible wavelength shift of as little as 0.15 nm. By tilting the FPE, the laser emission could be fine-tuned by 1 pm with an uncertainty of the spectral position of 0.5 pm. Figure 3 shows the fine-tuning by a series of interferograms. The analyz-

** Subsequently, the pumping efficiency was considerably increased by using a PEK-Labs flashtube, type XE 1-3. Peak output powers of 70 kV were obtained at a pump energy of 60 J (0.3 μF, 20 kV).

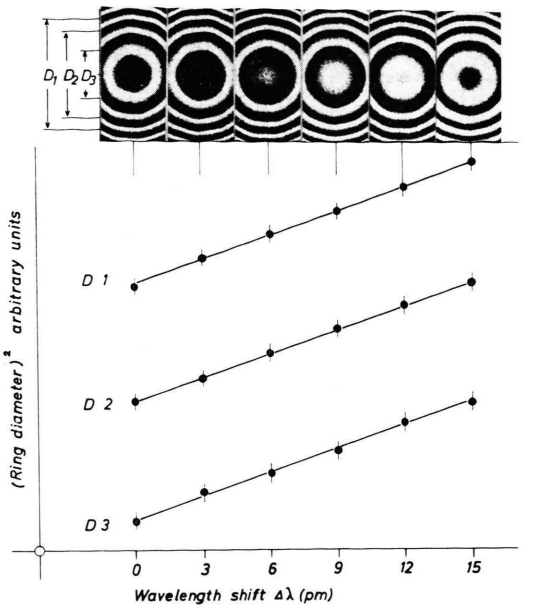

Fig. 3. Interferograms and results of densitometric analysis thereof showing fine tuning in steps of 3 pm.

ing Fabry-Perot interferometer had a plate spacing of 10 mm, corresponding to a free spectral range of 18 pm at 600 nm. The laser output remained practically constant when the FPE was inserted provided that the angle of incidence was kept within the interval 0.5° to 2.0°. For angles of incidence less than 0.5°, the high reflectivity coating acted as resonator mirrors, splitting the ring laser into a ring-shaped linear laser with the concomitant increase of the spectral bandwidth [4]. In the present experiments, the free spectral range of the intracavity FPE (0.58 nm) was less than the prism preselector bandwidth. Therefore, occasionally two lines of almost equal intensity were observed. In further experiments an FPE of 1 nm free spectral range will be used.

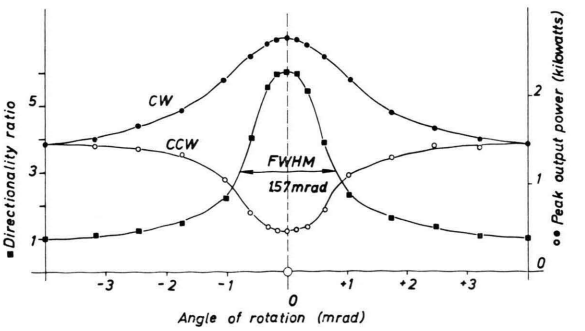

Fig. 4. Output power of clockwise (CW) and counterclockwise (CCW) traveling waves and resulting directionality ratio as a function of rotation of beam splitting output prism near feedback position.

The beam-splitting output prism was used to achieve travelling wave operation of the ring laser. By observing the far field, the clockwise (CW) and counterclockwise (CCW) travelling waves in the resonator could be brought into spatial coincidence by rotation of the beam-splitting prism. Figure 4 shows the output power of the CW and CCW emission and the resulting directionality ratio as a function of the angle of prism rotation. In the case of a symmetric position of the output prisms relative to the laser cuvette, as shown in Fig. 1, the directionality ratio (ratio of clockwise to counterclockwise output) was found to be 6 : 1. The output in the travelling wave mode of operation exceeded by 10% the sum of the uncoupled CW and CCW output. The directionality ratio was reduced to half its maximum value by rotating the prism from the central position to +0.8 or −0.8 mrad. This FWHM value of 1.6 mrad is almost equal to the above mentioned beam divergence angle. This property is the object of further investigation.

We thank Dr. M. PILTCH for a critical reading of the manuscript. The work was supported by the Fonds der Chemischen Industrie and the Deutsche Forschungsgemeinschaft.

[1] B. H. SOFFER and B. B. MCFARLAND, Appl. Phys. Letters **10**, 226 [1967].
[2] P. P. SOROKIN, J. R. LANKARD, and V. L. MORUZZI, Appl. Phys. Letters **15**, 179 [1969].
[3] D. J. BRADLEY, G. M. GALE, M. MOORE, and P. D. SMITH, Phys. Letters **26 A**, 378 [1968].
[4] F. P. SCHÄFER and H. MÜLLER, Opt. Commun. **2**, 407 [1971].
[5] L. RINGWELSKI, Dissertation, Universität Marburg 1971.
[6] M. HERCHER, M. YOUNG, and C. B. SMOYER, J. Appl. Phys. **36**, 3351 [1965].
[7] J. KUHL, G. MAROWSKY, P. KUNSTMANN, and W. SCHMIDT, Z. Naturforsch., paper accepted for publication [1972].
[8] W. SCHMIDT, W. APPT, and N. WITTEKINDT, Z. Naturforsch. **27 a**, 37 [1972].

Abklingzeiten und Radiolumineszenzausbeuten von Styrenlösungen PPO im Polymerisationsprozeß

M. GRODEL und Z. POLACKI

Physikalisches Institut der Technischen Hochschule, Gdańsk

(Z. Naturforsch. **27 a**, 713—715 [1972]; eingeg. am 22. November 1971)

In der Arbeit werden Szintillationszeiten und Radiolumineszenzausbeuten von Styrenlösungen PPO beim Polymerisationsprozeß mitgeteilt. Es wurde festgestellt, daß sich die Abklingzeit mit dem Konversionsgrad wie folgt ändert: der Anfang- und Endwert ist $\tau = 3{,}9 \cdot 10^{-9}$ s, dagegen beträgt der Maximalwert für den Konversionsgrad $\sim 50\%$ $\tau_{max} = 10^{-8}$ s.

Die Fluoreszenz von Styrollösungen einiger Luminophore während des Polymerisationsprozesses wurde bei Anregung mit γ-Strahlen von KRENZ [1] und von WEINREB und AVIVI [2] untersucht. Die Ergebnisse zeigten eine Änderung der Radio-Lumineszenzausbeute und der Übertragungsausbeute während des Polymerisationsprozesses. Weitere derartige Messungen [3, 4] lassen die Nützlichkeit solcher Untersuchungen für die Beurteilung des Einflusses der Polymerisationsbedingungen bei festen Polystyrollösungen erkennen. In der vorliegenden Arbeit wurden Abklingzeiten und Radiolumineszenzausbeuten während der Polymerisation von Styrollösungen mit 2.5-Phenyloxazol (PPO) gemessen.

1. Experimente

Styrol der Chemischen Werke Oświęcim (Polen), nagereinigt durch Destillation bei niederem Druck, und 2.5-Phenyloxazol (PPO) von Nuclear Enterprises, Edinburgh (G.-B.) (szintillationsrein) wurden in zylindrischen Pyrexbehältern (25 mm Durchmesser) einer thermischen Polymerisation unterzogen. Das Volumen der polymerisierten Substanz betrug 15 ml. Die relative Radiolumineszenzausbeute wurde a) aus dem mittleren

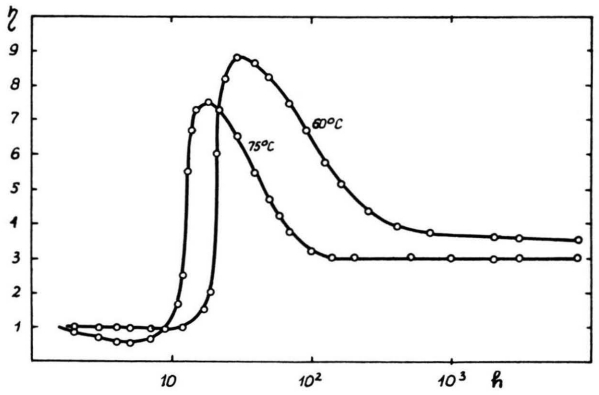

Abb. 1. Abhängigkeit der Radiolumineszenzausbeute (η) von der Polymerisationszeit (t) der Styrenlösungen PPO ($C_{PPO} = 4{,}5 \cdot 10^{-3}$ M/l; h = Stunden).

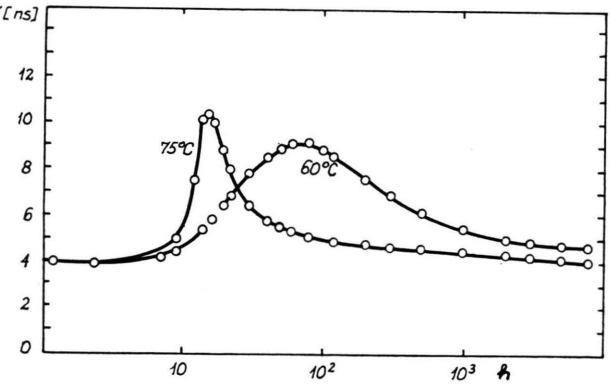

Abb. 2. Abhängigkeit der Szintillationsdauer (τ) von der Polymerisationszeit (t) der Styrenlösungen PPO ($C_{PPO} = 4{,}5 \cdot 10^{-3}$ M/l; h = Stunden).