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Bistable Operation of a Dual-Wavelength Synchronously Mode-Locked cw Dye Laser

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Abstract. Bistable operation of a dual-wavelength synchronously mode-locked cw dye laser is reported. Wavelength switching is found to depend on the pump power and the dye laser cavity lengths.

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Synchronously mode-locked cw dye lasers have proved to be reliable sources for pulses tunable over a wide range without the limitations of saturable absorbers [1]. There has been interest recently in generating synchronised pulse trains at two independently tunable wavelengths [2]. Such a system can be used to study (*a*) internal energy relaxation in molecules [3] by exciting at one wavelength and probing with delayed pulses at a longer wavelength (*b*) Raman vibrations [4] by exciting simultaneously with two pulses whose difference frequency matches the bond under investigation. The usual method of obtaining synchronised pulse trains at two wavelengths has been to excite two parallel cw dye laser with a common mode-locked ion laser. An alternative method is to construct a dual-wavelength dye laser such that two synchronously mode-locked lasers share a common gain medium as well as a common pump laser. When the dye laser cavities are each twice as long as the pump laser's and each contains only one pulse, then the dye pulses can be alternatively amplified. With a shared gain medium, however, there also exists the possibility that instead of operating simultaneously in two wavelengths, the laser may switch to one wavelength or may switch between wavelengths. In this note, we describe such an extended cavity, dual-wavelength, dye laser and this latter wavelength bistability. The dual-wavelength mode-locking of the system is presently under investigation and will be reported elsewhere.

The experimental arrangement is shown in Fig. 1. A basic Rhodamine 6G cw dye laser was converted to dual-wavelength operation by the addition of a Brewster's angle prism and two plane high-reflectivity mirrors. The mirrors were mounted on separate translation stages and the overall length of each dye-laser cavity was twice that of the argon-ion pump laser (1.09 m). The reflection from one face of the prism served as a collinear and superimposed output for both wavelengths. In single-wavelength mode-locked operation minimum average pump powers of ~ 60 mW were required for threshold. The two plane mirrors were in practice much closer than is suggested in Fig. 1 such that almost all of the dye lasing spectrum could be used and by rotation of the mirrors, the yellow and red cavities could each be tuned over almost half of this, e.g., λ_Y : 570–594 nm, λ_R : 611–650 nm. In the experiments to be described, the yellow and red wavelengths were 583 nm and 612 nm, respectively.

'Stable' bistable operation of the system could be achieved by careful adjustment of the dye-laser parameters. In this mode the system operated at only one wavelength and when this cavity was blocked, lasing commenced in the other, and vice versa. Two stable states exist when the net round-trip gains at the two wavelengths are almost balanced. The homogeneous nature of the dye's gain spectrum then ensures that once established, the laser operates in one wavelength until a gross imbalance is created between the two cavities. It is likely that the switching time is governed by the cavity lifetime which could be reduced to ~ 40 ns.

The first type of bistability was observed when both cavity lengths were held constant, e.g., $\Delta L_Y = 0.59$ mm and $\Delta L_R = 0.10$ mm, where the zero position corresponds to the cavity length for minimum threshold. Figure 2 shows the behaviour of the system, as the input power was increased from below threshold. The system lased in the red from threshold to 450 mW and

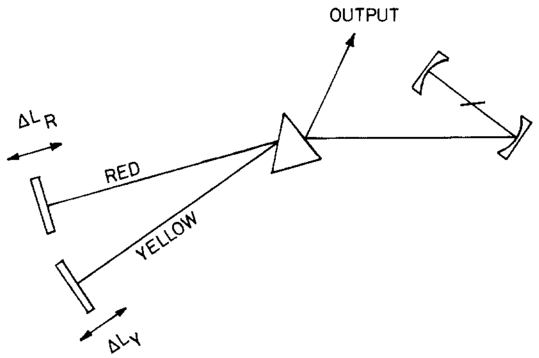

Fig. 1. Dual-wavelength cw dye laser

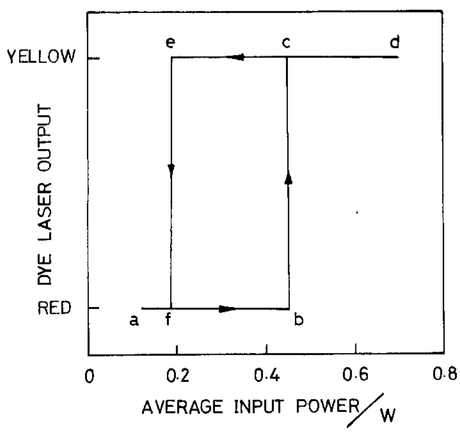

Fig. 2. Dependence of dye laser wavelength on average input power from mode-locked argon-ion laser

then switched to the yellow (path a b c d). As the pump power was decreased, the laser followed path d e f a giving rise to the characteristic hysteresis of bistability such that bistable operation could take place for pump powers in the 190–450 mW range. The switching to yellow at higher pump powers may be understood by considering the shift in the gain maximum of the dye to shorter wavelengths with increased excitation. The self-absorption in the dye remains almost constant with pumping and overlaps the short-wavelength end of the fluorescence band and thus the net gain moves from the red to the peak of the profile in the yellow at high pump powers. Similar tuning behaviour has been observed in free-running untuned dye lasers in which the output wavelength is observed to be a function of excitation [5]. It should be noted that it is not necessary to employ synchronous pumping to observe bistability of this form.

The second type of bistability was observed at a constant input power level with one cavity length fixed while the other was adjusted in length. Figure 3 shows the dependence of the lasing wavelength on the length of the red cavity when the yellow cavity was 0.5 mm longer than optimum and the input power was 260 mW. As L_R increased, the system followed path

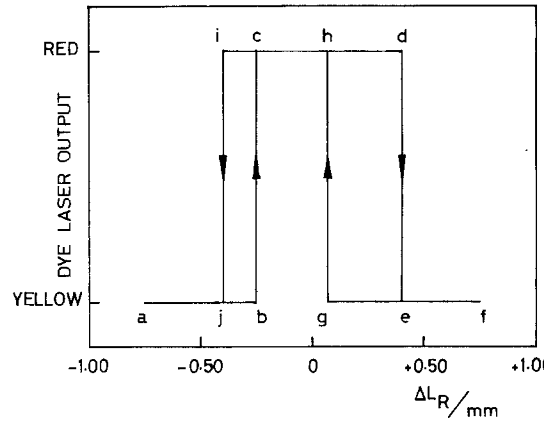

Fig. 3. Variation of dye laser wavelength with change in length of the red cavity. Yellow cavity length held constant at $\Delta L_Y = +0.5$ mm

a b c d e f and as it decreased, path f g h i j a was followed giving rise to two bistable regions and thus an anti-clockwise and a clockwise loop. Switching occurred reproducibly for increments at the resolution limit (5 μm) of the translation stage/dial gauge combination being used to adjust the cavity lengths. Similar behaviour was observed when the yellow cavity was held constant less than the optimum and also for the complementary situations in which the red cavity length was fixed. In all cases the lengths were changed slowly and the system was allowed to stabilise between steps. This switching behaviour can be explained by considering the direction of the switching. In Fig. 3 in the region of $\Delta L_R \sim 0$ the system switches to the red, as the red cavity then presents a lower threshold. At large values of $|\Delta L_R|$ the yellow cavity is closer to its optimum and thus the system lases in the yellow. The opposing conditions apply when the red cavity length is held fixed and the yellow is varied. Due to the dye-laser cavities being each twice the length of the pump laser cavity, there would be two pulses contained in the lasing cavity when the system is operating at one wavelength.

The bistable behaviour of a dual-wavelength synchronously mode-locked cw dye laser has been described. A full investigation of this phenomenon is necessary before a true dual-wavelength dye laser can operate in which bistability is completely eliminated. The effects discussed are also novel examples of optical bistability in general, and are not limited to the dye laser.

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