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PHASE AND FREQUENCY DYNAMICS IN A BIDIRECTIONAL RING LASER

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Résumé - L'alternation des modes dans les lasers circulaires bidirectionnels devient plus claire si l'on étudie la dynamique des phases et fréquences des deux modes. Les effets dynamiques entre autres sont "mode-pushing", "mode-pulling" et des changements brusques de phase s'élevant à π radians.

Abstract - Mode alternation in bidirectional ring lasers is more clearly understood by examining the dynamics of the phases and frequencies of the two modes. Dynamical effects include mode-pushing, mode-pulling and phase jumps of π radians.

1 - INTRODUCTION

Homogeneously broadened ring lasers which can support a single mode in each direction may operate in unidirectional, bidirectional, or pulsed modes depending on the various mechanisms of coupling between the modes. We have investigated the pulsing states for a laser model appropriate generically to CO₂, Nd:YAG, ruby and semiconductor ring lasers in which the polarization can be adiabatically eliminated. In an earlier publication /1/ we found thresholds for the transition from stable steady state unidirectional operation to pulsing, and we presented a variety of examples of the pulsing behavior.

More recently we have investigated the dynamics of the mode phases and frequencies in the pulsing regime. We originally supposed that there might be frequency dynamics from mode pulling interactions (as in a laser with an injected signal) when one mode was injected into the other after scattering from the Bragg grating formed in the population inversion by the standing wave bidirectional field. Different mode frequencies were presumed to originate from different losses due to asymmetries in the two unidirectional modes. Such loss differences would lead to different mode-pulling of the unidirectional solutions and therefore to an initial frequency mismatch.

In contrast, although we have found that laser cavity detuning is essential for the spontaneous pulsations in these lasers, we have also found that the pulsations do not rely on frequency differences in the unidirectional steady state solutions. Pulsing is observed in a completely symmetric laser. Our studies of the phases and frequencies of the two modes reveals that there is dynamical mode-pushing and mode-pulling which is a key part of the interaction /2/.

2 - RESULTS

We consider first the mode-alternation form of pulsing which appears for small cavity detunings and for pumping rates that exceed the instability threshold by only small amounts. The dynamics in the intensity appear to be only simple square wave switching as shown in the intensity plots of Figures 1a and 1b. Careful examination shows that the switching is irregular with ten to twenty percent fluctuations in the times between switches. In addition, a magnification of the signals as shown in Figs. 1c and 1d reveals that there is modulation of both beams. As the modes approach the unidirectional steady state solution of

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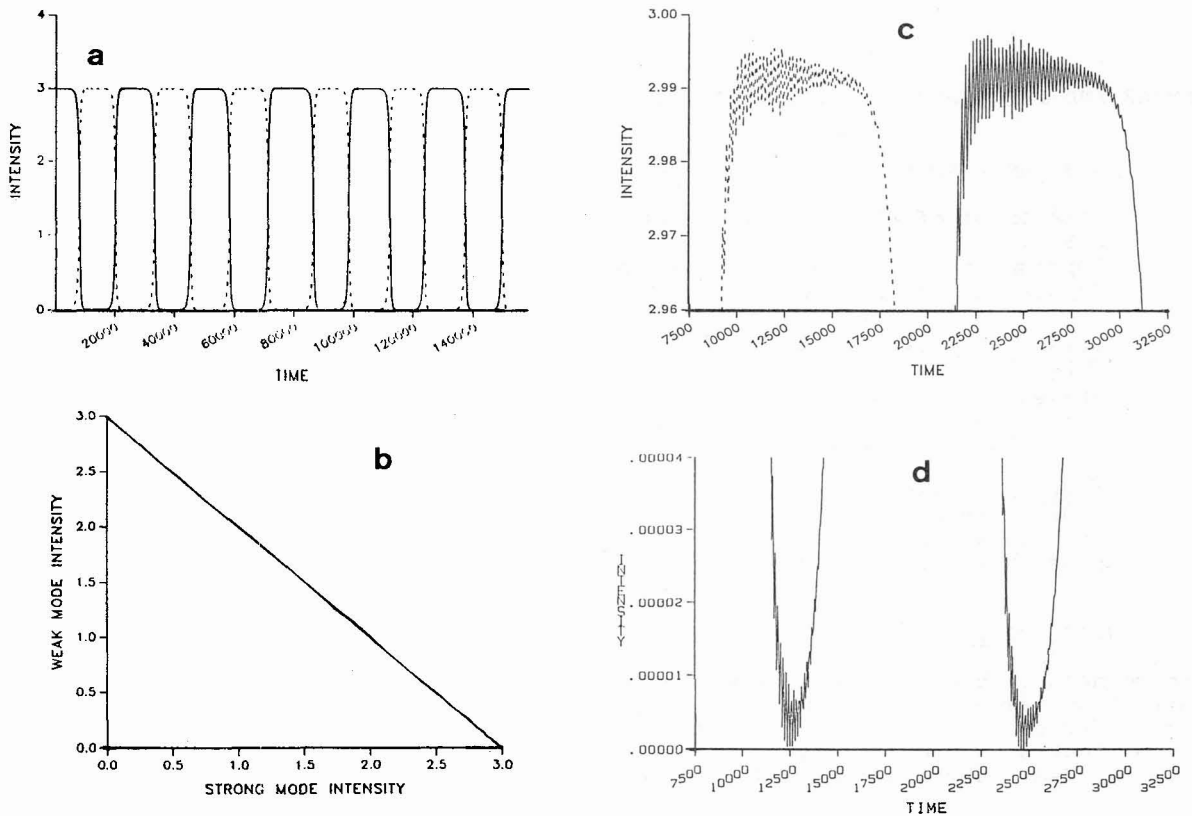


Fig. 1. Intensities of the two counterpropagating modes for $A = 4$, $K = 1.4 \times 10^7$, $\gamma_{\parallel} = 2.5 \times 10^3$, $\Delta = 0.1$. a) Intensities versus time. b) I_1 versus I_2 , c) enlargement of strong intensity region versus time region, d) enlargement of weak intensity region corresponding to c).

one mode on and one mode off they are modulated by the relaxation oscillation frequencies given by $\Omega_{R+} = \sqrt{2K\gamma_{\parallel}(\bar{A}-1)}$ and $\Omega_{R-} = \sqrt{4K\gamma_{\parallel}(\bar{A}-1)}$, where (+,-) refer to the strong and weak mode intensities, respectively; κ is the cavity decay rate; γ_{\parallel} is the population inversion decay rate; and \bar{A} is the pumping rate divided by $1 + \Delta^2$, where Δ is the cavity detuning measured in units of the homogeneous linewidth. The threshold value of the pumping rate for laser action at $\Delta = 0$ is unity.

When the weak mode arrives very close to zero intensity, its mean intensity begins to grow and the strong mode displays an abrupt increase in the amplitude and complexity of its modulation. This occurs because the weak mode field has abruptly switched both its phase and its optical carrier frequency. These switches are shown in Figure 2. Figure 2a shows the dynamics of the frequencies of the two modes; Figure 2b shows the phase difference of the two modes; Figure 2c shows the total phase of the three complex variables of the problem (the two modal amplitudes and the amplitude of the spatially sinusoidal modulation of the population inversion); and Figure 2d shows the phase of the grating amplitude.

When a mode is dominant it assumes the steady state operating frequency of Δ . Relative to that steady state frequency, when a mode is growing in intensity it has a frequency that is closer to the atomic resonance frequency and when a mode is decaying it has a frequency that is further from the atomic resonance frequency. This mode-pushing and mode-pulling is a dynamical effect resulting from the phase shifts induced by the portion of the field of the other mode which is scattered by the Bragg grating and mixed with the mode in question.

The total phase of the system is relatively constant except where one mode or the other passes near zero. Here the phase shifts by π radians. This shift correlates with the transition of the trajectory of the solution from the stable (contracting spiral) manifold near the fixed point to the unstable (expanding spiral) manifold. Physically this represents a phase shift of the weak field so that instead of there being destructive interference with the scattered strong field there is now constructive interference.

The difference of the phases of the two modes also shows that a gyroscopic detector of the motion of the fringe pattern (formed by interference of the two modes) would give signals suggesting nearly periodic reversals in the rotation rate of the laser. In fact, there is no rotation, only dynamically induced frequency shifts of the modes.

These dynamical frequency shifts also cause the model we are using to be more appropriate than might be assumed at first glance. The approximation of the longitudinal spatial hole-burning by a sinusoidal function remains valid only if the product of the modal amplitudes is small compared to the saturation intensity. Surprisingly we find the amplitude of the holes burned in the population inversion does not become more than a few percent of the mean value of the inversion even when both modes are strong. This results because the frequency differences of the modes cause the spatial interference pattern to move longitudinally, effectively washing out the hole-burning effect.

Similar phase and frequency dynamics are observed for other forms of pulsing (both periodic and chaotic) for other laser parameters as shown in /2/. Experimental evidence of this type of behavior has recently been found in bidirectional FIR lasers and will be reported elsewhere /3/.

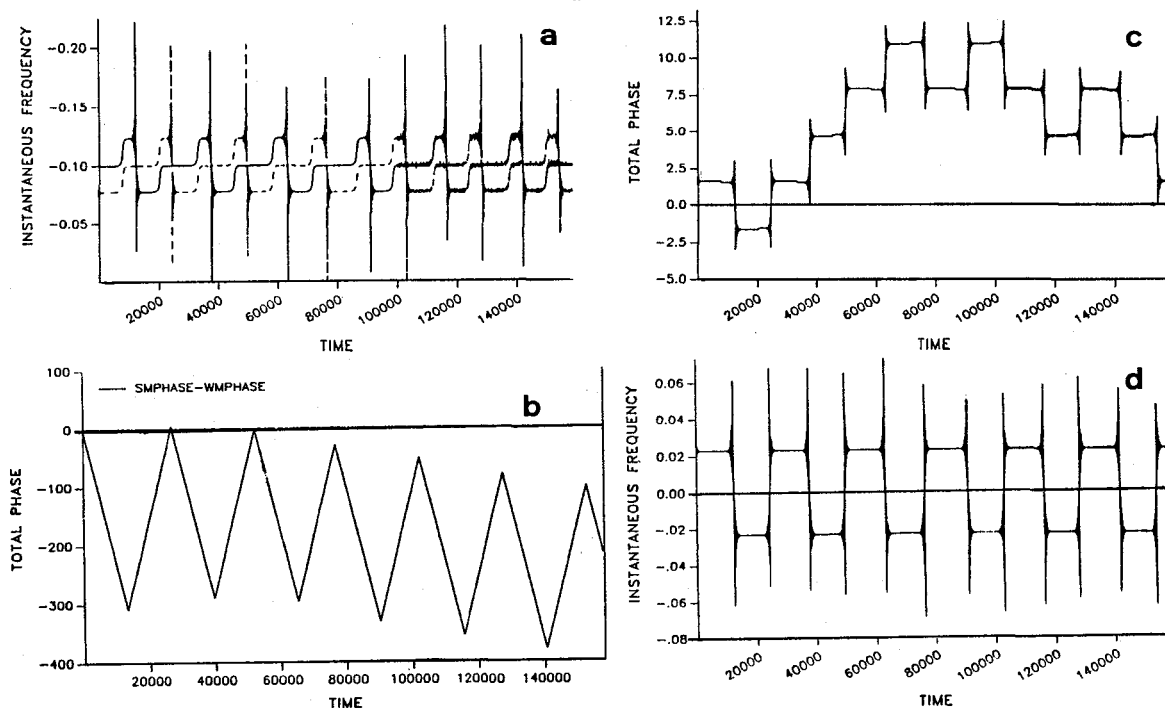


Fig. 2. Phases and frequencies of the two modes. a) Frequencies $\dot{\phi}_1$ and $\dot{\phi}_2$ (of modes I_1 and I_2) versus time, b) $\phi_1 - \phi_2$ versus time, c) $\phi_1 - \phi_2 + \Psi$ where Ψ is the phase of the population grating, d) $\dot{\Psi}$ versus time.

3 - ACKNOWLEDGEMENTS

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