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Control of ring lasers by means of coupled cavities

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Abstract:
Variable phase coupling to an external ring is used to control a unidirectional ring laser. The observed behavior of the coupled rings is explained theoretically.

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Coupling of optical cavities offers a means of controlling the properties of one cavity (e.g. a laser) by making adjustments to another, external cavity. In this contribution we consider a unidirectional ring laser (bow-tie laser) coupled to an external ring cavity. Using different configurations we can control the out-coupling from the ring laser thereby influencing the threshold and operating point of the laser. This may be used to match the output coupling strength to the internal losses in the laser, optimizing the power output. It is also possible to choose a circulating power level that provides the best balance between the passive losses and a nonlinear loss such as e.g. conversion to the second harmonic.

We have found experimentally that by quickly changing the phase of the feedback from the external ring it is possible to Q-switch the ring laser. Also, at certain values of the phase of the feedback in the external ring, instabilities in the total system occur and oscillations arise in the ring laser.

The theoretical description involves the solution of a set of transcendental nonlinear equations, one for the laser, one for the second harmonic generation and one for the output coupling. The coupling is controlled by the transmission properties of the coupled FP-ring. We believe the facilities of modern PC-based mathematics programs offer new possibilities for quickly and conveniently solving these equations and obtain information on the complex behavior of coupled nonlinear resonators that have so far not been available.

We consider first the general case of two coupled rings shown in Fig. 1. The equation for the laser is

$$P_{p,sdl} = \frac{h\nu_{sdl}}{\tau_c}\frac{l_e}{c}\left(\frac{2P_i}{h\nu_{dpl}} + \frac{V_a}{\sigma l \tau}\right).$$

This expression gives the pump power, $P_{p,sdl}$, needed to produce a circulating laser power, P_i. Here σ denotes the stimulated emission cross section, $h\nu_{sdl}$ the pump photon energy, $h\nu_{dpl}$ the laser photon energy and c the speed of light. l is the crystal length, l_c is the geometric cavity length, V is the mode volume and $V_a = (l/l_c)V$ is the volume of the mode inside the active medium. We also define an effective optical path length $l_e = l_c + (n-1)l$, where n is the index of refraction of the active medium. Further $\tau_c = l_e/(\alpha c)$ is the lifetime of the laser photons in the cavity and τ is the excited state lifetime. α is the total distributed loss per pass containing contributions from absorption, mirror transmissions and second harmonic conversion. We denote explicitly the total internal losses including absorption, scattering and mirror transmission by α_i and the conversion to second harmonic by $\alpha_{SHG} = (P_{c4} - P_{c3})/P_{c4}$. In relation to Fig. 1 we can identify P_i with $(P_{c3} + P_{c4})/2$, and $P_{p,sdl}$ with pp.

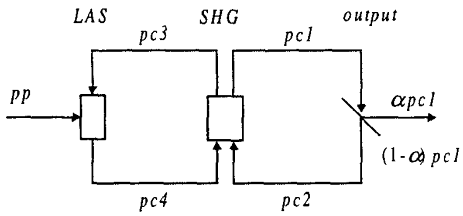

Fig. 1. Principle of coupled ring cavities.

For the coupling to the second ring we consider two cases: Coupling through nonlinear conversion to the second harmonic and coupling through dielectric mirrors.

For the coupling through the conversion to the second harmonic we use the relations [1]:

$$P_{c1} = P_{tot}\tanh^2[gz_0 + gz_c]$$

$$P_{c3} = P_{tot}\,\mathrm{sech}^2[gz_0 + gz_c]$$

where

$$gz_0 = \tanh^{-1}\left[\sqrt{\frac{P_{c2}}{P_{tot}}}\right] \text{ and } P_{tot} = P_{c2} + P_{c4}\,.$$

The gain is proportional to the square root of the total power, $g = c_2\sqrt{P_{tot}}$, where c_2 is a materials constant characterizing the actual SHG-crystal.

Inserting gz_0 we can write

$$P_{c1} = P_{tot}\tanh^2\left[\tanh^{-1}\left[\sqrt{\frac{P_{c2}}{P_{tot}}}\right] + gz_c\right]$$

$$P_{c3} = P_{tot}\,\mathrm{sech}^2\left[\tanh^{-1}\left[\sqrt{\frac{P_{c2}}{P_{tot}}}\right] + gz_c\right].$$

In case of ordinary output coupling by a dielectric mirror we have $P_{out} = R\,P_{c1}$ and $P_{c2} = (1-R)P_{c1}$, where R is the power reflectivity of the output mirror.

However, in coupled resonators, the reflectivities of the dielectric coupling mirrors depend on the field incident from the return beam. In general, the complex electric field reflectivity of any mirror in the ring depends on all the others:

$$\frac{E_r}{E_i} = f(r_1, r_2, r_3, r_4, r_5, r_6, \Phi_1, \Phi_2)\,,$$

where r_i is the reflectivity of the i'th mirror and Φ_j is the total phase in the j'th ring. The functional form depends on the configuration. We thus have to solve the coupled field equations including the variable mirror reflectivity to see the effect of the feedback. When the rings include nonlinear effects, like the laser gain, second harmonic generation or sum/difference generation, we must solve a set of simultaneous transcendental equations. This has been done by means of a PC-version mathematics program.

We have specifically considered a bow-tie unidirectional ring laser coupled to a triangular ring as shown in Fig. 2. At first we consider the coupled rings without the KTP second harmonic crystal. Experimentally, we vary the phase by means of the manual control box, which in turn varies the apparent reflectivity of the mirrors M5 and M6. We can for instance cause the laser to go below threshold by adjusting the phase of the feedback loop in such a way that the reflectivities of M5 and M6 become high. We can also adjust the phase of the return path such that the output from the mirror M7 is optimized.

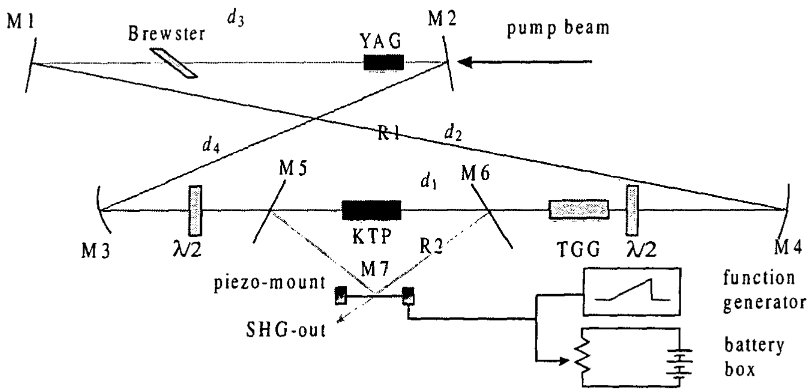

Fig. 2. Unidirectionl ring laser coupled to a triangular ring cavity.

If the phase is made to change quickly, the ring laser is observed to Q-switch just by means of the variable phase control. We have also observed oscillations in the system at certain steady-state adjustments of the phase of ring R2 relative to the phase of ring R1. The waveform of the oscillations are similar to the pattern derived in [2].

In a further development we consider the coupled rings with the KTP-crystal inserted. The SH generation now depends on the phase of the return sh-signal. By varying the piezo-mirror, we can measure the effect of a phase variation in the feedback.

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