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Self-stabilizing additive-pulse mode-locking due to thermo-optical non-linearity in an optical fiber

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Abstract. In additive-pulse mode-locked (APM) lasers, an interferometric phase match of both coupled cavities must normally be maintained with the help of an electronic servo loop. However, Cheung et al. [Opt. Lett. **16**, 1671 (1991)] described a Nd:YLF APM laser which somehow automatically adjusted the relative resonator phase. We reproduce this behavior and analyse its origin. Thermal effects due to the light power guided in the fiber affect the effective fiber length, which in turn influences the phase and thus the power level; hence a closed servo loop results. We demonstrate this explanation to be correct in quantitative terms. Consequences arise for other systems involving fiber-optic loops or interferometers.

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Additive-pulse mode-locking (APM) [1], also called coupled-cavity mode-locking [2], is a passive mode-locking technique in which pulse width reduction is obtained through intracavity interference of two versions of the pulse that differ in their chirp. One of the two coupled resonators contains a nonlinear element providing self-phase modulation, usually an optical fiber. The pulse gets chirped in the fiber and then interferes with the other pulse from the gain resonator. Conditions can be found in which the interference is constructive in the pulse center but destructive in the wings, resulting in a net pulse shortening. Since this process occurs on every cavity round trip, the pulses are narrowed down efficiently until other limitations to pulse width, such as finite gain bandwidth, become important. Interest in this kind of operation began with the soliton laser [3]; for a historical and an experimental account, see [4] and [5], respectively.

In order to maintain the relative phase of both pulses as required for this process in the presence of acoustic vibrations, thermal drift etc., mere passive stability is insufficient. A suitable electronic servo loop was first described in [6]. It derives an error signal from the time-averaged power in the fiber and acts on a PZT for cavity length adjustment accordingly. This circuit has been constructed in many laboratories since. Incidentally, it has been shown that instead of the average power in the fiber, its square is also suitable and may, in some cases, be advantageous [4, 5, 7].

Recently, Cheung et al. [8] reported continuous pulse operation of their lamp-pumped Nd:YLF APM laser for some hours without any electronic stabilization. This phenomenon clearly depended on improved passive stability (the laser head was acoustically isolated to reduce vibrations due to turbulent cooling water flow). Equally clearly, passive stability alone could not explain this behavior: APM operation was maintained even when the length of one of the resonators was intentionally varied over several wavelengths, or the difference in the round trip phase (relative phase) over several multiples of 2π, provided that the variation was not too rapid. Obviously, there must be some kind of internal regulating mechanism in this experiment. Its inability to compensate for rapid variations indicates a time scale of a few seconds.

A similar phenomenon was reported by Groninga and Harde [9], who observed both a lamp-pumped and a diode-pumped Nd:YAG APM laser to self-stabilize in a similar manner. They arrived at the conclusion that a thermal mechanism in the gain medium was responsible.

We reproduced the behavior reported by Cheung et al. [8] with a lamp-pumped Nd:YLF APM laser. We fully confirm all essential experimental findings. This includes the observation that the phenomenon only exists if a careful vibration isolation of the laser head is in place. It also includes the system's insensitivity to deliberate large length perturbations, as long as they occur slowly enough.

Automatic tracking of the phase angle between two resonators requires, out of necessity, that at least one of the resonators adjusts its phase according to some criterion that depends on the operational state of the laser. There are thus two questions: (1) Which resonator is responsible – the control cavity, the gain cavity, or both? (2) What is the criterion that leads to an error signal? It is unlikely that such a slow mechanism depends on "fast" processes such as the Kerr effect, gain saturation, etc. On the other hand, it is well known that the time-averaged intracavity power is a useful criterion for an error signal. It seemed conceivable that the intracavity power, which is of the order of several watts, could affect the resonator length, possibly through a thermal mechanism. We find that this reasoning is justified. Experimental studies show that, indeed, thermal effects due to the light power guided in the fiber affect the effective fiber length, which in turn influences the phase and thus the power level; hence a closed servo loop results. Quantitative measurements support this interpretation. While we make no claims about the viability of this self-stabilization from an applications point of view, we believe that the phenomenon at least warranted an explanation.

1 Laser experiments

Figure 1 schematically shows the APM laser considered here. It is based on a lamp-pumped Nd:YLF laser (Quantronix model 4217), operating at 1053 nm. As a modification of the original setup, we first fitted an acoustical isolator between the laser head and the base, to reduce vibration. This consists of a pad of high-density styrofoam between the laser head and the bench, plus elastic clamps to hold the head in place. This modification turns out to be crucial for the topic under discussion here; as pointed out above, a similar observation was made in [8]. Otherwise, the setup is quite conventional (compare [1, 4, 5]): the main cavity is coupled to a control resonator of the same round trip time, such as to form a Fabry–Perot geometry. The control resonator contains 98 cm of standard telecommunications fiber as a non-linear element. A-spherical lenses (Corning) are used for coupling into the fiber, and the fiber power throughput can reach 70%. Note that with a measured fiber cutoff wavelength of 1248 nm, both LP_{01} and LP_{11} modes can propagate. The laser output is taken from the control resonator via a polarizing beam splitter. A half-wave retarder preceding the beam splitter is rotated slightly so that an adjustable fraction of light (typically 15%) is passed through towards the fiber. We do not use a second polarizer as is often done [10]; note that it would increase the losses in the fiber cavity. It turns out that the self-stabilization discussed here does not work if such a second polarizer is used.

The optical fiber is mounted on a three-coil polarization controller [11], which is adjusted for maximum finesse of the fiber resonator. The tight bending radius causes noticeable losses for the LP_{11} modes.

This laser is able to deliver self-stabilized pulse operation over extended times, e.g. half an hour, during which time no interruptions other than a few drop-outs of less than a second occur. Remarkably, in order to achieve this mode of operation, the adjustment of the fiber input coupling lens needed to be slightly away from the position of maximum power throughput, while at the other fiber end we adjusted the retroreflector (lens plus mirror) for optimum efficiency at all times.

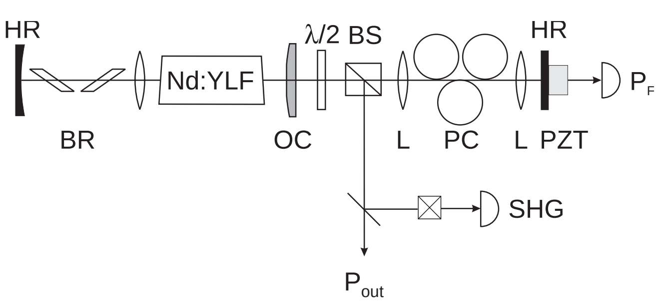

Fig. 1. The setup of our APM laser. HR, high reflector; BR, Brewster plates; OC, 12% output coupler; BS, beam splitter; L, aspheric lenses; PC, polarization controller; PZT, piezo-transducer; SHG, second harmonic signal

2 Observations about the self-stabilizing action

To trace the mechanism for self-stabilization, we externally perturbed the length of the fiber resonator by means of a PZT-mounted mirror. A voltage ramp is applied such that the phase scans through several multiples of 2π. We define the relative phase ϕ such that it increases when the length and thus the round trip phase of the fiber resonator increases. With a four-channel digital oscilloscope, the ramp itself, the output power, the second harmonic of the output power and the power in the fiber were monitored simultaneously with a temporal resolution of the order of microseconds. The second harmonic signal serves to identify times at which the laser produces pulses. The phase shift and its rate of change can be calibrated from the 2π-periodic laser output signal.

We first applied a "rapid" perturbation ($|\mathrm{d}\phi/\mathrm{d}t| \approx 2\pi/50\,\mathrm{ms}$), to eliminate the self-stabilization. We noticed a remarkable correspondence: During pulsing episodes, the power in the fiber varies with a definite trend as the phase is ramped on. While this behavior cannot be seen very clearly in every single shot due to noise, it is very clearly reproducible in an average sense (Fig. 2). On average, we find a gradient of $\mathrm{d}P_\mathrm{F}/\mathrm{d}\phi = (-290 \pm 80)\,\mathrm{mW/rad}$. (There are hysteresis effects in the onset of the APM action, which depend on the direction of the scan, and result in slightly lower values for the downward ramp. The number quoted is the total average; the large error results in part from this spread.)

Next, we used a "slow" perturbation ($|\mathrm{d}\phi/\mathrm{d}t| \approx 2\pi/5\,\mathrm{s}$). This was slow enough for the self-stabilization to take over control, and even scans of 4π did not interrupt the APM pulsing mode of operation. We still observe a trend in the

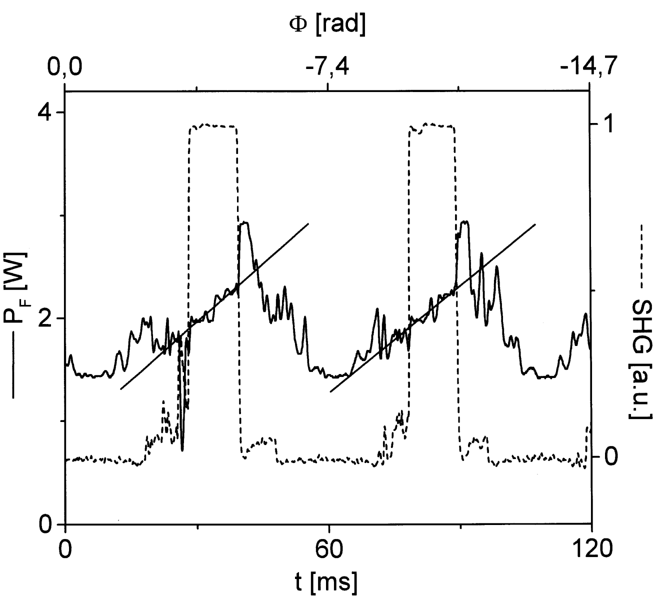

Fig. 2. The solid line shows the dependence of the power in the fiber resonator on a fast imposed phase shift. The dotted line shows the SHG signal indicating the phase range of the mode-locking

intrafiber power with phase of the same sign as above, but the value is much smaller: $(-31 \pm 3)\,\mathrm{mW/rad}$ on average (Fig. 3). In what follows, we will give an interpretation of the reduced slope with respect to the rapid scan.

We thus clearly see a dependence of the intrafiber power on the relative resonator phase. The question is whether this phase-dependent power can introduce power-dependent phase changes.

3 Thermooptical effects in fiber

To investigate this possibility, we set up a Mach–Zehnder interferometer separately from the laser. In one arm of the interferometer we placed a 30 cm piece of fiber taken from the same spool as the laser fiber. This fiber was also bent into a loop similar to that of the laser fiber in the polarization controller. Light from the laser, which now operated in cw mode (conventional single cavity operation), was sent into this interferometer. The beam was first manually blocked. After unblocking it, we looked for “running” fringes that would indicate path length changes. However, at optimum launch conditions for LP_{01}, no clearly discernible fringe movement was found. Also, longitudinal maladjustment of the coupling lens did not change this situation. On the other hand, the slightest lateral maladjustment immediately produced “running” fringes. It is noteworthy that only the radial maladjustment was found to matter, not its azimuth. The direction of the fringe shift gives the sign of this derivative: we invariably find an increase in optical path length after turn-on.

At a certain lateral maladjustment we obtained fringe patterns as in Fig. 4, from which the amount of the induced phase change is determined along with the pertinent time constant by fitting the function

$$\phi(t) = \phi_0 + \Delta(1 - \mathrm{e}^{-t/\tau})\,. \tag{1}$$

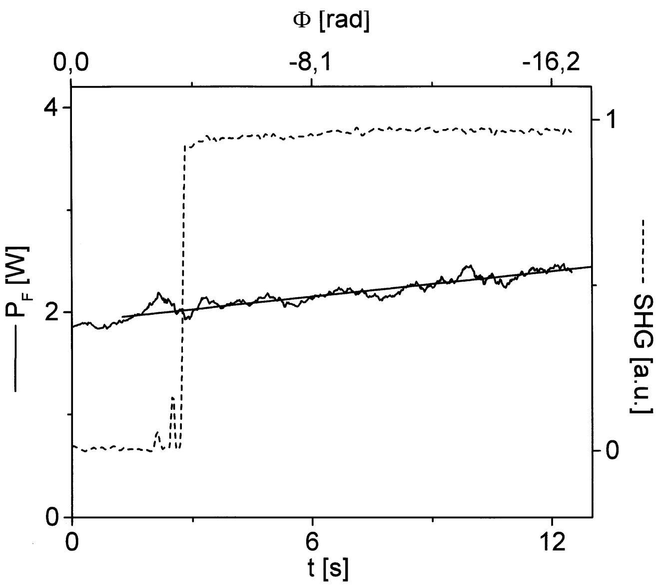

Fig. 3. The solid line shows the dependence of the intrafiber power on a slow imposed phase shift when the laser is self–stabilizing. The dotted line shows the SHG signal indicating mode-locking

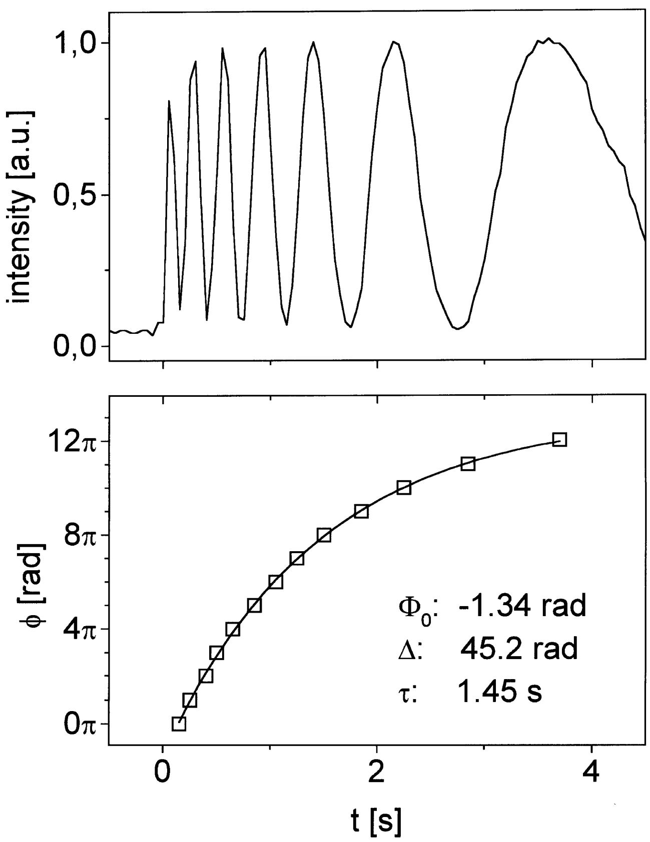

Fig. 4. Top: a turn-on transient of Mach–Zehnder interferometer transmission. Bottom: the thermally induced time evolution of the phase

Here, ϕ_0 is the (random) initial phase, Δ is the asymptotic value of the induced phase shift and τ is the time constant. In spite of the simplicity of (1), we obtain a good fit to the data. Figure 5 demonstrates the critical dependence of Δ on lateral adjustment. To avoid the difficulties connected with a precise and repeatable measurement of the lateral shift, we used

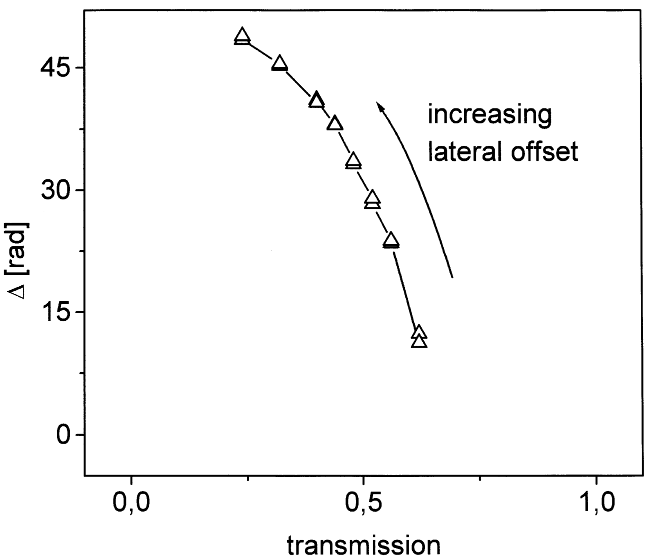

Fig. 5. The dependence of the asymptotic phase shift on lateral misalignment

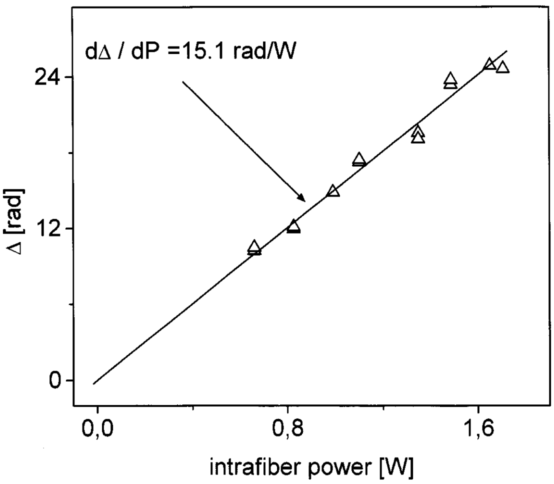

Fig. 6. The power dependence of the asymptotic phase shift

the total fiber throughput as a measure of lateral maladjustment. For a fixed lateral maladjustment (throughput reduced from an optimum at 65% to 58%), the measurement was repeated for several intrafiber power levels P_F to obtain $\Delta(P_F)$ (see Fig. 6). Note that Δ increases in proportion to P_F with a significant slope of $d\Delta/dP_F = +15.1$ rad/W.

We interpret this result as follows: as long as the launch spot is circularly symmetric to the fiber core, there is no excitation of the LP_{11} modes due to their odd symmetry. Even a small lateral maladjustment suffices to couple some power into the LP_{11} modes. This power easily leaks out into the coating at the tight bends in the polarization controller and is dissipated in the lossy coating material. The fraction of the dissipated power is geometry-dependent, not power-dependent. This dissipation locally heats the fiber and causes it to expand in proportion to P_F. Due to the thermo-optical effect, an increase in power then leads to a proportional increase in phase. Thermo-optic coefficients of typical fibers are given in [12, 13]; we assume 30 ppm/K. Thus, for example, we can estimate the temperature rise of the fiber (considered to be uniform) over a bending length of 5 cm induced by an intrafiber power change of 200 mW to be approximately 0.2 K, which is a reasonable order of magnitude.

The time constant τ obtained from (1) is found to be independent of power, as expected for a linear heat conduction problem. Its value is 1.4 ± 0.2 s, which again is reasonable for a thermal effect. It is also in accordance with the observations in [8].

We verified directly that the observed phase changes are due to thermal effects. To this end, we measured the temperature of a tight fiber loop by taping it on to the surface of a thermopile sensor salvaged from an optical power meter. An absolute calibration in degrees is difficult to obtain with any accuracy due to thermal contact problems etc., and therefore the vertical scale in Fig. 7 is in arbitrary units.

As we could not determine the exact lateral offset in a micrometer range, we measured the total throughput instead, which decreases monotonously with increasing offset. It is clear enough, however, that the increase in the measured temperature with adjustment away from optimum is steep first, goes through a maximum and then falls very steeply again. (In this case different lenses were used for coupling, and the throughput was limited to 50%.)

Also shown in Fig. 7 (solid line) is the expected LP_{11} excitation efficiency (assuming a mode matching which allows optimum ground mode coupling efficiency for the case of a centered launch spot) calculated from an overlap integral of an irradiated Gaussian beam with a known mode profile (see, e.g., [14]).

For the calculated curve the transmission is $0.5\,(\eta_{01} + \alpha\eta_{11})$, in which $\eta_{01(11)}$ denotes the excitation efficiency of the $LP_{01(11)}$ modes, and α accounts for residual transmission of the LP_{11} mode. Choosing $\alpha = 0.15$ yields the best fit, as shown in Fig. 7. The factor of 0.5 accounts for the limited coupling efficiency due to imperfect imaging. It is obvious that the agreement with the data points is good. This confirms the interpretation that dissipation of part of the energy carried by the LP_{11} modes is responsible for the heating. Beyond the maximum, the misalignment is so large that a significant fraction of the total power is coupled into the cladding, and dissipated in the coating over the first centimeters, where the metal chuck sinks all heat.

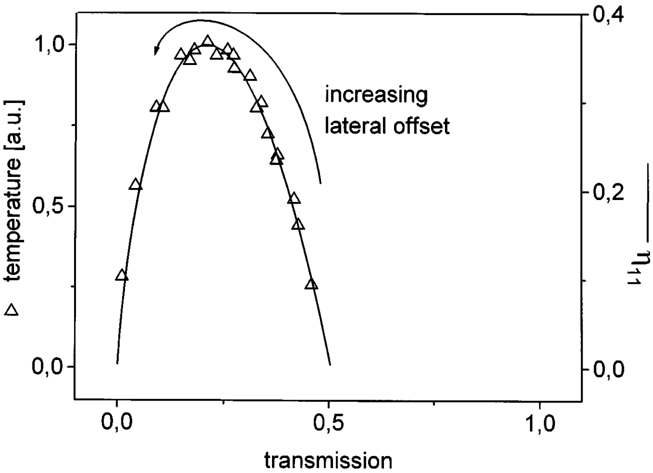

Fig. 7. The symbols show the measured temperature rise of a fiber loop due to lateral misalignment. The solid curve shows the calculated excitation of LP_{11} as a function of lateral misalignment

4 Thermooptical effects in the gain medium

One might well assume that variations in the relative resonator phase ϕ are caused by phase changes in the gain resonator, rather than in the control resonator. To assess this possibility, we set up a Mach–Zehnder interferometer with a 632 nm He:Ne laser, which had the laser gain medium in one of its arms, as a light source. In measurements similar to those in Fig. 4, we recorded the phase shift in the gain medium as a function of the pump power provided by the arc lamps. It turns out that the phase shift is unmeasurably small even after the resonator is fully blocked to bring the power down to zero. Only when we completely turned off the power supply of the arc lamps could we measure phase shifts of the order of 20 rad (at the He:Ne laser wavelength!) over a few seconds. This indicates that $d\Delta/dP \ll 1$ rad/W, which definitively rules out power-dependent phase shifts as the responsible mechanism in our laser.

5 The control loop

So far, we have shown that the power in the fiber depends monotonously on ϕ and vice versa. A shortening of the fiber resonator results in an increase in the intrafiber power; this increased power leads to a stronger heating of the fiber, and the resulting thermal expansion tends to compensate for the shortening. Dissipation will occur predominantly at the fiber ends where cladding modes become excited; however, as pointed out above, the temperature rise at the fiber ends is reduced by thermal contact with the metal chucks. Also, dissipation is expected at tight bends, e.g. in the polarization controller, because it is there that higher-order core modes experience losses.

This is similar to the conventional APM laser servo loop [6], except that the feedback of the power on to the resonator length is not accomplished by an electronic circuit but by a thermal mechanism.

We write $A_L = \mathrm{d}P_F/\mathrm{d}\phi$ and $A_F = \mathrm{d}\phi/\mathrm{d}P_F$ for short. The round trip phase ϕ is written as $\phi = \phi_0 + \mathrm{d}\phi_{th} + \mathrm{d}\phi_{ext}$, where a constant ϕ_0 takes into account the fiber length at the equilibrium temperature, $\mathrm{d}\phi_{th}$ denotes phase shifts caused by dissipation of power guided in the fiber, and $\mathrm{d}\phi_{ext}$ denotes phase perturbations due to other (environmental) causes. Since

$$\mathrm{d}P_F = A_L\,\mathrm{d}\phi = A_L\,(\mathrm{d}\phi_{ext} + \mathrm{d}\phi_{th}) \tag{2}$$

and

$$\mathrm{d}\phi_{th} = A_F\,\mathrm{d}P_F\,, \tag{3}$$

one has, in the closed control loop,

$$\frac{\mathrm{d}P_F}{\mathrm{d}\phi_{ext}} = \frac{A_L}{1 - A_F A_L}\,. \tag{4}$$

This quantity was measured directly; see Fig. 3. The closed loop will suppress external phase perturbations according to

$$\frac{\mathrm{d}\phi}{\mathrm{d}\phi_{ext}} = \frac{1}{1 - A_L A_F}\,. \tag{5}$$

Note that the denominator of the last two equations is larger than unity because $A_L < 0$. We thus obtain the well-known result that, in a closed negative feedback loop, external perturbations are suppressed by approximately the reciprocal of the loop gain $|A_L A_F|$.

$\mathrm{d}P_F/\mathrm{d}\phi$ was obtained from a scan so rapid that stabilization could not follow; this amounts to an open loop measurement. We may therefore identify the result with A_L and we find that $A_L = -0.3\,\mathrm{W/rad}$. The value for A_F is obtained from the Mach–Zehnder interferometer result of $\mathrm{d}\Delta/\mathrm{d}P_F = 15\,\mathrm{rad/W}$ by observing that in the laser, which is a Fabry–Perot cavity, the effective phase change is twice the single transit value due to forward and backward propagation. Thus, $A_F = 30\,\mathrm{rad/W}$. This yields a loop gain of $A_F A_L = -9$.

Therefore, external phase perturbations should perturb the intrafiber power by $\mathrm{d}P_F/\mathrm{d}\phi_{ext} = -30\,\mathrm{mW/rad}$, and the relative resonator phase by $\mathrm{d}\phi/\mathrm{d}\phi_{ext} = 0.11$. The former was measured directly; the result of $(-31 \pm 3)\,\mathrm{mW/rad}$ is in perfect agreement. The latter can be compared to the reduction in the observed A_L in the open loop measurement and the corresponding measurement at closed loop (slow scan), which also amounted to a factor of 0.11. Again, the agreement is convincing. Moreover, we find experimentally that in the absence of the thermal self-stabilization effect (i.e. with rapid scanning), the APM action occurs over a ϕ interval of about 1.6 rad, which is similar to other lasers (compare with [5]). This implies that external perturbations can amount to $1.6\,\mathrm{rad} \times (\mathrm{d}\phi_{ext}/\mathrm{d}\phi) \approx 15\,\mathrm{rad}$ before pulse formation ceases. This agrees well with the observation that an external perturbation of up to 14 rad does not interrupt the pulse stream.

6 Conclusions

In conclusion, self-stabilization and insensitivity to externally imposed phase shifts in our APM laser result from the interplay of energy transfer to the fiber resonator and thermo-optical effects caused by higher-order core modes. It is conceivable that even with a single mode fiber, which would have to have losses at some sharp bends, similar stabilization is possible. In fact, we tried this with a different fiber, which is strictly single-mode at the emission wavelength. While some indication of a stabilizing action could be seen, the control was not nearly as successful, and continuous stable operation over an extended time was not obtained.

A similar mechanism observed in a diode-pumped laser was attributed to thermal effects in the gain medium [9]. There is no contradiction here. In fact, it is worth pointing out that the type of pump makes a great difference. In lamp-pumped systems, about 6 kW of lamp power is dissipated. The heat is removed by rapid coolant flow, so that the rod surface temperature remains below that of boiling water. In other words, the power-dependent temperature change is roughly $\mathrm{d}T/\mathrm{d}P_{abs} \leq 60\,\mathrm{K}/6\,\mathrm{kW} = 10\,\mathrm{mK/W}$. Any variation in light power in the crystal, even between zero and the maximum laser intracavity power, hardly affects the crystal temperature, because heat is so efficiently removed. In diode-pumped systems, with their good pumping efficiency, however, the intracavity power forms a significant fraction of the total light power in the crystal. Changes in power level may well lead to a noticeable temperature change, since here the corresponding estimate would be $\mathrm{d}T/\mathrm{d}P_{abs} \leq 60\,\mathrm{K}/10\,\mathrm{W} = 6\,\mathrm{K/W}$, or 600 times more.

The main disadvantage of the kind of internal phase stabilization described here is that one has no means of assuring that the laser is operating in the middle of the range over which the APM action takes place; the initial phase is picked at random. This adversely affects the reproducibility of the effect. While we do not, therefore, anticipate technical applications of this phenomenon, we would like to point out that thermal mechanisms may adversely affect other applications as well. Fiber-optic loops and resonators will play an important role in many possible applications of photonic technology. The situation reported here makes it clear that such systems will potentially be affected by self-heating effects that may have surprising and unforeseen consequences. Typically, lower power levels will be involved than in the present case, and also fibers will be single-mode, so that a lesser fraction of the power can be dissipated. Nevertheless, as demands on such technology grow, it is probable that the finesse of fiber resonators will be increased; this will then indeed raise the issue of thermal stability. At that point, the relevance of this report will go far beyond the curious behavior of a particular laser.

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