Passive mode locking of homogeneously and inhomogeneously broadened lasers

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We describe self-starting passive mode locking of a cw inhomogeneously broadened laser and compare its characteristics with those of a passively mode-locked homogeneously broadened laser using different Nd-doped glasses as the active material. Broadband gain media with homogeneously broadened transitions are found to be superior to those broadened inhomogeneously for passively mode-locked lasers.

Passive mode locking (PML) of cw lasers has been a powerful technique for the generation of subpicosecond and femtosecond optical pulses. From a practical point of view, it is important that the PML process be self-starting because this eliminates the need for active starting mechanisms, reducing cost and complexity of the ultrashort pulse lasers. Necessary conditions[1,2] and a threshold power of intracavity radiation[3,4] have been derived for self-starting PML operation of cw lasers. Recent developments in ultrafast solid-state lasers have revealed great differences in the behaviors of different systems. Whereas PML has been realized easily in homogeneously broadened lasers,[5] ultrashort-pulse generation in inhomogeneously broadened systems has relied on external initialization of mode locking.[6–8] This has not been well understood because inhomogeneously broadened lasers are expected to be more easily mode lockable than their homogeneously broadened counterparts.[9]

The purpose of this Letter is to find explanations for these unexpected experimental facts. The use of Nd-doped glasses as the active medium offers a unique possibility of investigating homogeneously and inhomogeneously broadened lasers under the same experimental conditions because the dominant line-broadening mechanism is different in different glass hosts,[10] whereas there are only minor variations in the main spectroscopic parameters such as wavelength, linewidth, fluorescence lifetime, and absorption and emission cross sections. Following this idea, a cw Nd:glass laser has been built by using different Nd-doped glasses. This research led to self-starting PML of a cw inhomogeneously broadened laser (Nd:silicate glass) for what is to our knowledge the first time. Replacing the gain material by Nd:phosphate glass has enabled us to characterize passively mode-locked operation of homogeneously and inhomogeneously broadened lasers under the same operation conditions. The experimental results are found to be in good agreement with the predictions of a unifying theory of self-starting PML.[3]

The experimental setup is shown in Fig. 1. A standard coupled-cavity laser containing a single-mode optical fiber in the auxiliary resonator has been constructed. In the limit of zero fiber dispersion, the nonlinear coupled cavity may be viewed as a termination with a power-dependent reflectivity. For moderate powers the dynamic change in reflectivity can be expanded to first order in $P(t)$,[2]

$$\Delta R(t) = \kappa P(t), \qquad (1)$$

where $P(t)$ is the instantaneous intracavity power incident upon the nonlinear termination (see Fig. 1) and κ can be calculated by using the theory of additive-pulse mode locking.[11] With the parameters listed in Fig. 1, we obtained $\kappa = 2.0 \times 10^{-5}\ \mathrm{W}^{-1}$. The laser is pumped by the infrared lines (752–799 nm) of a krypton laser. With a Nd:silicate glass slab (Schott LG 680, length 4 mm, Nd^{3+} concentration 3 wt. %) and the coupled cavity blocked, the output power is ≈0.1 W at a pump power of 0.8 W. The spectrum of the free-running silicate laser exhibits large fluctuations and has a typical bandwidth of ≈8–10 nm. Comparison of this value with the fluorescence linewidth of ≈30 nm clearly demonstrates the dominant role of inhomogeneous broadening in this laser material. The insertion of a 50-μm-thick uncoated étalon results in a more stable spectrum and reduces the oscillating bandwidth to ≈0.5 nm. The spectrum consists of $m \approx 1.4 \times 10^3$ longitudinal modes within the FWHM.

With the étalon in the (main) cavity, the silicate laser becomes passively mode locked when the phase of the auxiliary cavity is properly adjusted. The threshold intracavity power for self-starting is $P_{\mathrm{th}} \approx 0.8$ W. When pumped with $P_p = 0.8$ W, the laser produces pulses of 1.4-ps duration with an average output power of 25 mW. The pulses have a slight chirp as revealed by the fringe-resolved autocorrelation trace in Fig. 2, and the number of axial modes in the mode-locked state is $m_{\mathrm{ml}} \approx 2.5 \times 10^3$. Although the coupled-cavity silicate laser self-starts easily with the étalon in the resonator, we have been defeated in our attempts to mode lock the laser in the absence of additional bandwidth limitation even at intracavity powers as high as $P \approx 2$ W.[12]

When the Nd:silicate glass slab is replaced by a Nd:phosphate glass slab (Schott LG 760, length

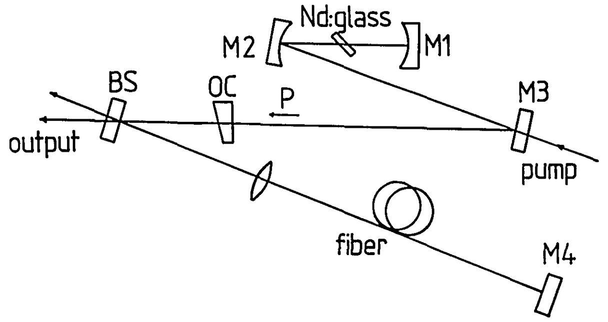

Fig. 1. Schematic diagram of the passively mode-locked Nd:glass lasers. M2, M2, high-reflectivity mirrors with radii of curvature of 7.5 and 15 cm, respectively; M3, dichroic plane mirror; OC, output coupler with 90% reflectivity; BS, beam splitter with 84% reflectivity; M4, high-reflectivity plane mirror. The single-mode fiber has a length of 1.8 m, and the auxiliary resonator is twice as long as the main resonator.

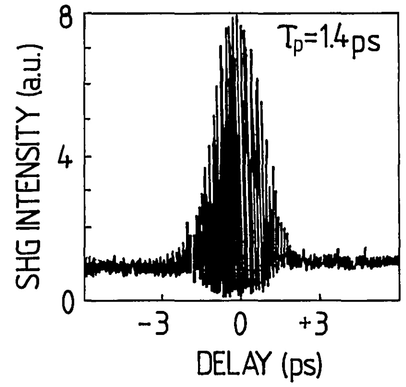

Fig. 2. Interferometric autocorrelation trace of the output of the Nd:silicate glass laser. SHG, second-harmonic generation.

5 mm, 2% dopant concentration) having a gain bandwidth of ≈20 nm, the width of the optical spectrum of the free-running laser decreases to $\Delta\lambda \approx 0.1$ nm (corresponding to $m \approx 2.7 \times 10^2$), without inserting any additional bandwidth-limiting elements in the cavity. This is the consequence of a broad effective homogeneous linewidth of the 1.053-μm Nd transition in this host at room temperature.[10] With the auxiliary cavity blocked, the phosphate laser delivers a cw output of ≈0.2 W when pumped with 0.8 W of power. The higher performance can be attributed to the better thermal characteristics of the phosphate glass.[10] PML easily self-starts in the coupled-cavity phosphate laser without any additional bandwidth limitation for $P > P_{\mathrm{th}} \approx 1.4$ W. Interestingly, the steady-state mode-locking characteristics (pulse width, bandwidth) are nearly the same as in the silicate laser. Because the effective gain bandwidth is in excess of 10 nm in both PML lasers, the pulse duration is limited in both cases by group-velocity dispersion of the fiber rather than by the bandwidth of the oscillator.

The fact that a reduced number of modes in the cw laser facilitates achieving PML operation is rather surprising. The peak power $P \ln(m)$ of the most intense (mode-beating) fluctuation[3] yields a dynamic change of $\approx -\kappa P \ln(m)$ in the round-trip loss, suggesting that the initial fluctuation starts growing at a higher rate in a laser with more axial modes initially oscillating. However, in real laser systems there are always effects opposing the evolution of an intense single pulse from the free-running oscillation. In fact, the initial fluctuation tends to be destroyed by uncorrelated phase perturbations to the axial modes and uneven shifts of their eigenfrequencies.[3] Frequency shifts depending nonlinearly on the mode index may originate from dispersion and/or spurious reflections in the cavity. These effects contribute to a broadening of the beat notes in the rf spectrum of the laser. The rate of pulse destruction is linearly proportional to the linewidth of the first beat note centered at ν_0, the mode spacing at gain center, and the condition for the cw laser to become passively mode locked can be written as[3]

$$\kappa P \ln(m) > \pi T_R \Delta\nu_{3\mathrm{dB}}, \tag{2}$$

where T_R stands for the cavity round-trip time and $\Delta\nu_{3\mathrm{dB}}$ is the 3-dB full width of the first beat note of the free-running laser. In physical terms, the fractional increase in the peak intensity of the initial fluctuation during one round trip (left-hand side) must exceed the fractional decrease in peak intensity owing to the pulse-destroying effects discussed above (right-hand side) for mode locking to prevail. Typical beat-note lines of the silicate laser with and without a 50-μm étalon are shown in Figs. 3(a) and 3(b), respectively. Both spectra are subject to significant fluctuations, which are attributed principally to those in the optical spectrum of the laser. With the étalon in the laser, $\Delta\nu_{3\mathrm{dB}} = (3 \pm 1)$ kHz. Within experimental uncertainties, this is the same value as obtained in the phosphate laser without an étalon, which, on substitution into relation (2), pre-

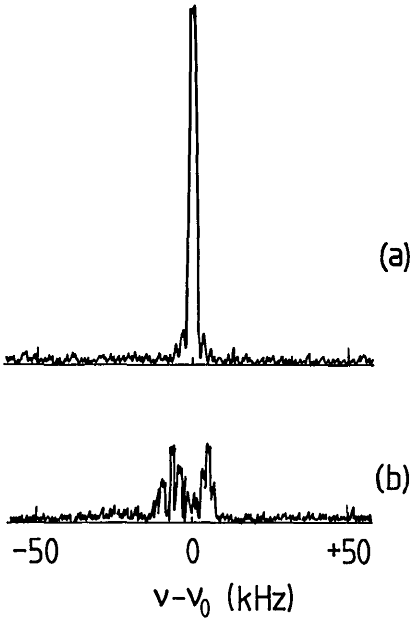

Fig. 3. Radio-frequency spectra of the free-running Nd:silicate laser around its first beat note of $\nu_0 \approx 100$ MHz (a) with and (b) without a 50-μm étalon in the cavity. The resolution bandwidth of the spectrum analyzer was ≈0.5 kHz. The integrated powers in (a) and (b) are the same within the experimental accuracy.

dicts thresholds of $(1.3 \pm 0.4) \times 10^{-5}$ and $(1.7 \pm 0.6) \times 10^{-5}$ for κP in the silicate and phosphate lasers, respectively. Experimentally we have obtained $(\kappa P)_{\mathrm{th,Si}} \approx 1.6 \times 10^{-5}$ and $(\kappa P)_{\mathrm{th,Ph}} \approx 2.8 \times 10^{-5}$, in reasonable agreement with the theoretical predictions. Removing the étalon from the silicate laser gives rise to a broader and necessarily weaker beat-note spectrum fluctuating within a bandwidth of $\Delta\nu_{3\mathrm{dB}} = (20 \pm 10)$ kHz. It is clear by inspection that the intracavity dispersion of $<10^3$ fs^2 cannot account for this substantial broadening. Whereas the broader optical bandwidth increases the pulse-buildup rate by less than a factor of 1.5 (owing to the greater number of modes), pulse destruction is speeded up much more by the substantially broadened beat-note linewidth. Consequently, self-starting PML calls for a significantly higher κ and/or P in this case. Even broader beat-note linewidths have been measured in inhomogeneously broadened fiber lasers,[8] which may be attributed to spurious intracavity reflections[3] inherent in open fiber oscillators. However, in the (bulk) lasers under consideration, the interaction of the modes with the amplifier seems to be the dominant effect in broadening the beat-note spectrum because $\Delta\nu_{3\mathrm{dB}}$ is found to depend sensitively on the saturated round-trip gain.[5]

In conclusion, we have demonstrated self-starting passively mode-locked operation of a cw inhomogeneously broadened laser and compared its characteristics with those of a homogeneously broadened laser. Elementary considerations suggest that ultrashort-pulse formation should be more easily achievable in inhomogeneously broadened lasers, in which the already oscillating modes only have to be pulled into synchronism, than in corresponding homogeneous systems, in which the same steady-state pulse width requires modes to be generated in addition to those oscillating in the free-running laser.[9] Our experimental results are in contradiction with this prediction. The reason for this discrepancy is the uneven frequency spacing between axial cavity modes due to random and/or deterministic frequency-pulling effects in real laser oscillators. More free-running modes imply mode spacings spread out over a broader frequency range (beat-note line broadening), increasingly impeding mode locking. In the time domain, this expresses itself in a reduction of the lifetime of the initial mode-beating fluctuation from which the mode-locked pulse should evolve, requiring a higher intracavity power and/or nonlinearity for self-starting PML. Although it is possible to increase this lifetime and achieve self-starting by reducing the effective gain bandwidth, this may, in general, impair steady-state mode-locking performance. By contrast, homogeneously broadened lasers support a comparatively low number of longitudinal modes under free-running conditions, resulting in long-lived mode-beating fluctuations and thereby in a low threshold for self-starting passively mode-locked operation. The ultimate mode-locking performance is not at all affected by the small number of free-running modes because after their locking the loss modulation becomes sufficiently strong to generate a large number of properly locked modes for ultrashort-pulse production. In summary, laser materials with broadband homogeneously broadened transitions are optimum gain media for passively mode-locked lasers, whereas broadband inhomogeneously broadened lasers require a careful spectral control if mode locking is to be accomplished.

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