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Spectrum Narrowing and Frequency Smooth Tuning in CW Ring Ti:Sapphire/Dye Lasers with Solid Etalon

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Abstract

An optimal set of selectors for single-frequency generation in continuously widely tuneable ring lasers was experimentally identified. This set consists of two elements: a three-component birefringent filter with plate thickness ratios of 1:4:13 to minimise side band transmission peaks, and a solid quartz Fabry–Pérot étalon with a thickness of a few millimetres. Using a commercial compact high-speed galvanometer driver to tilt the latter also enables automatic locking of the étalon's transmission peak to the cavity mode and allows continuous (mode-hop free) frequency tuning in the GHz range.

Keywords: single-frequency tuneable laser; frequency selection; contiguous sweeping laser frequency

1. Introduction

Selection of the emission spectrum in continuous wave (CW) lasers with a broad gain bandwidth requires highly selective elements that exhibit relatively low nonselective losses [1]. These nonselective losses must be at least an order of magnitude lower than the optimal transmission of the output coupler, which in CW lasers may be a few per cent (for example, 3–5–10%). For this reason, devices such as diffraction gratings, which typically incur nonselective losses exceeding 10% [2], cannot serve as selectors in CW lasers.

The principle of narrowing the emission bandwidth of a tuneable laser consists of: (1) From the wide gain spectrum, a single longitudinal cavity mode (one emission frequency) is isolated; and (2) if required, its frequency is stabilised (the fluctuation range is reduced). Let us consider the first stage of this process—obtaining single-frequency operation in a CW tuneable laser—together with the question of whether a linear- or a ring-cavity configuration is more suitable for single-frequency generation.

It should be noted that the issue of spectrum selection in tuneable lasers has been the subject of many studies [1,3–9]; however, the majority of these works are now rather dated. Allow us to discuss this topic in the context of the present day situation and the capabilities offered by modern technology.

2. Single-Frequency Selection

Selection of a single longitudinal generation mode (frequency) in such broadly tuneable CW lasers with relatively long cavities—such as Ti:Sapphire or Dye lasers—requires a super narrowband selective element whose transmission peaks are spaced farther apart than the wavelength tuning range of the laser [1]. Ideally, this selective element should have a transmission function approximating a Dirac delta function [10] in the generation region and very low (preferably < 1–2%) nonselective losses. In practice, such an ideal element

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does not exist and is normally approached by a set of multiple selectors, the combined transmission function of which approximates the δ-function within the lasers' generation band [1].

The combined transmission function of the selector set is only a crude approximation to the δ-function; its sole important similarity with a true δ-function is the presence of a single, pronounced maximum peak within a broad spectral region. However, the combined transmission also exhibits small side peaks whose transmission is insufficient for lasing, so generation cannot occur at those frequencies. The fine selector provides the single dominant transmission peak (the operative one), while the rough selector suppresses the nonoperative transmission peaks of the fine selective element across the entire generation band (see Figure 1).

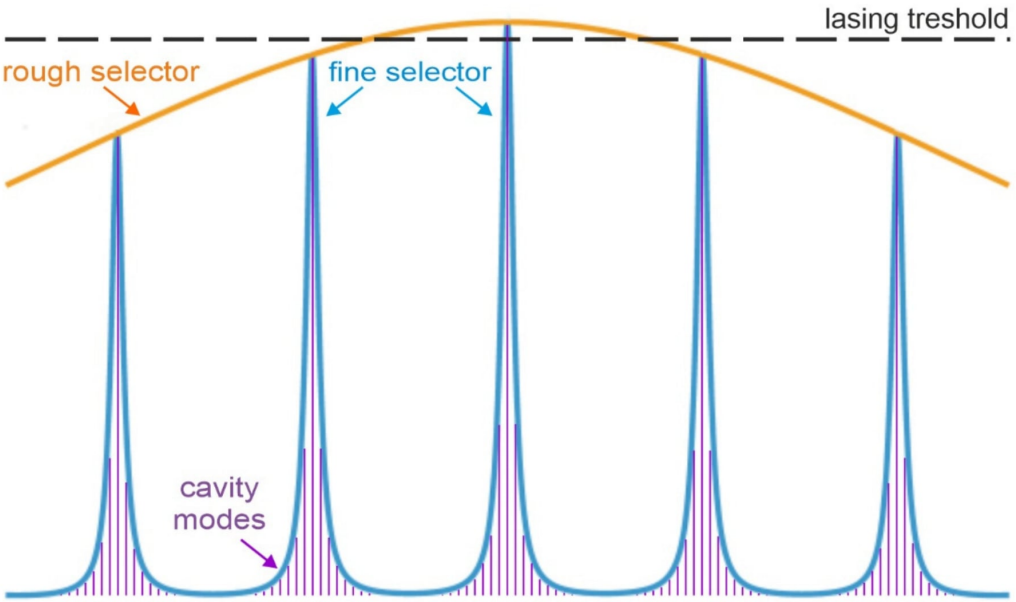

Figure 1. Selection of a single longitudinal laser cavity mode for a broad spectral gain profile of the active medium.

In principle, this combination of two elements (rough and fine selectors) can guarantee single-frequency operation of a broadly tuneable CW laser. The peculiarity is that a pair of selectors can, in theory, always yield single-frequency generation on some longitudinal cavity mode, but it does not always succeed to have it on the required resonator mode—or, equivalently, at the desired emission wavelength.

This is easy to understand. In order to create a single dominant transmission peak at a particular spectral location (within the laser's wavelength tuning range, of course), the transmission peaks of the fine and rough selectors must coincide. This coincidence can occur at a random point in the spectrum (or on a random longitudinal resonator mode). Achieving such overlap on a specific neighbouring longitudinal mode is practically impossible because the rough selector is only coarsely tuneable. To force generation at a required emission wavelength (or a specific longitudinal resonator mode), a third selector is sometimes added to the pair. This intermediate selectivity selector sits between the fine and the rough selectors. Triplet selector sets are employed in most broadly tuneable CW lasers. The rough selector is usually a birefringent filter, while the other two selectors are often a thin and a thick Fabry–Pérot étalons. The thick Fabry–Pérot étalon is the most selective element, and the thin étalon provides the intermediate selectivity that allows the single-frequency laser to be tuned to the desired wavelength.

If the only requirement is to obtain single-frequency laser generation without locking it to a particular optical wavelength, it is sufficient merely to overlap the transmission peaks of a rough and a fine (frequency-selective) selector. Single-frequency lasing will occur on the longitudinal cavity mode situated near the point where these peaks coincide. The fact that a longitudinal resonator mode will be present in the immediate neighbourhood of the overlap point of the rough- and fine-selector transmission peaks can be seen from the following estimates.

In Figure 1, the transmission peak of the fine selector encompasses roughly fifteen longitudinal cavity modes (at full peak width); this relatively small number is shown merely for illustration; in practice many more modes exist. Moreover, the fine-selector transmission peaks are not as sharp as depicted in the figure, which was drawn for clarity. For example, consider a fine selector implemented as a conventional Fabry–Pérot (F–P) interferometer. Even if it is built from two separate parts (e.g., two prisms [11]), its base is unlikely to exceed about 10 mm because as the base length increases, so does the difficulty of interferometer alignment. The spectral finesse F of the interferometer's transmission function depends on the reflectivity R of its partially reflective surfaces [12]:

$$F = \frac{\pi\sqrt{R}}{1-R} \tag{1}$$

where R—mirror reflectivity. For R = 0.3 this yields F $\approx$ 2.5.

For a linear F-P interferometer base of 10 mm, the free spectral range between transmission peaks is

$$\Delta\omega = c/2L \cong 15\ \text{GHz} \tag{2}$$

Hence the typical full width at half-maximum of a transmission peak is

$$\Delta\nu = \Delta\omega/F \cong 6\ \text{GHz} \tag{3}$$

The spacing between longitudinal modes of a linear resonator of length, say, L_1 = 0.5 m, is

$$\Delta\nu_2 = c/2L_1 = 300\ \text{MHz} \tag{4}$$

So approximately twenty longitudinal modes fall within the fine-selector transmission peak. Lasing will occur on the mode that lies closest to the coincidence of the rough- and fine-selector transmission maxima. Because the density of longitudinal cavity modes within the fine-selector bandwidth is relatively high, achieving single-frequency generation in long cavities depends less on tuning the selectors to a particular cavity mode and more on tuning the two selectors with respect to one another. When the maxima of the rough and fine selector transmission peaks are aligned, the laser will operate on the cavity mode that experiences the lowest losses; the frequency of that mode is essentially random.

To make the generated frequency well defined rather than random, a third (intermediate) selector is introduced, and a means of smoothly varying the cavity mode frequencies (e.g., by fine-adjusting the laser cavity length) is provided.

3. Linear and Ring Resonators

The advantages of ring cavities over linear ones for wavelength selection in tuneable lasers are well known [13–15]. Travelling wave evens out the spatial inhomogeneity of the population inversion that may be created in the field of a standing wave. By eliminating the spatial hole burning effect in the relatively short active medium of the laser (compared with the cavity length) [16,17] and by increasing the spacing between the longitudinal resonant modes (in a ring cavity $\Delta\nu = c/L$, whereas in a linear cavity $\Delta\nu = c/2L$, with L

being the cavity length), the requirements on the selectivity of the fine selector are relaxed. Consequently, the spectral finesse F of the F–P étalon used as the fine selector can be lowered, which in turn allows a reduction in the reflectivity of the étalon's surfaces and/or a shortening of its thickness. Both actions decrease the nonselective losses introduced by the fine selector, thereby increasing the single-frequency output power in a ring cavity.

It should be noted that the problem of single-frequency generation in bulk ring lasers is not limited to Ti:Sapphire/Dye lasers. In these systems, a coarse wavelength selector (birefringent filter) is introduced to narrow the generation spectrum to a width comparable to, or smaller than, that achievable with bulk ring lasers that possess a much smaller tuning range. Additionally, these lasers also frequently make use of a Fabry–Pérot etalon (uncoated or partially reflective) as a selector for the single-frequency operating regime [18,19]. This addition deliberately excludes fibre lasers, which have a different spectral-narrowing methodology [20].

A precise calculation of the required selectivity of the fine selector is unlikely to be possible (because several parameters are uncertain, including the nonparallelism and quality of the étalon's working surfaces, and the degree of alignment/misalignment of the whole cavity). Therefore, we will examine a few empirically validated configurations of fine selectors and Ti:Sapphire (Dye) laser cavities that provide relatively high power single-frequency generation.

The F–P étalon is chosen as the fine selector because of its relative simplicity, especially in the solid version. Various elements have been tried as fine selectors: a Michelson interferometer [21], a Fox Smith interferometer [22], a Mach Zehnder interferometer [23], a combination of highly reflective mirrors and a diffraction grating (a variant of the Michelson interferometer) [24], and others. The Fabry–Pérot interferometer turned out to be the most acceptable solution and is frequently used to achieve single-frequency laser output. Its advantages lie in the relative ease of adjustment when the interferometer contains reflecting surfaces belonging to separate components [11] or when no adjustment is required at all if the reflecting surfaces are on a single optical element (a solid étalon [25]). A F–P étalon with an air gap between the working surfaces is required to allow continuous spectral tuning of the transmission peaks in step with the tuning of the laser cavity's frequencies. Piezoceramic transducers (PZT) are often used for both types of tuning. The larger the frequency tuning range required for the laser, the shorter the étalon's base must be (the spacing between adjacent transmission peaks of the etalon must exceed the required continuous tuning range).

A few examples may be instructive. With air-gap spacing of a F–P interferometer of 10 mm, the spacing between adjacent transmission peaks is 15 GHz. With a base of 3 mm, the spacing increases to 50 GHz. If a 10 mm base interferometer is tuned in the 10–15 GHz range by tilting in the laser cavity, its output power experiences a rapid drop (due to a sharp rise in the interferometer's nonselective losses). By contrast, tilting a 3 mm base interferometer over the same frequency range can be done within a relatively small angular range, avoiding a significant loss of output power. A 10 mm base etalon is practically impossible to tune by tilting, therefore its base is adjusted with PZT [11], whereas a short base etalon (e.g., 3 mm) can be tilted using a compact modern analogue galvo driver.

Thus, we arrive at an optimal solution for a fine selector in tuneable lasers: a Fabry–Pérot étalon with a short base (for example, 3 mm), rotated by an analogue galvo driver, placed in a ring cavity. The remaining question is what spectral finesse (or coating reflectivity) the étalon must have to reliably isolate a single generation frequency across a wide range of output powers. As noted above, this cannot be determined analytically, so we will attempt to experimentally establish the required spectral finesse of the F–P interferometer used as the fine selector to achieve single-frequency operation in a volume tuneable laser.

The schematics of the studied CW ring cavity Ti:Sapphire laser and Dye laser [8,26,27] are shown in Figure 2.

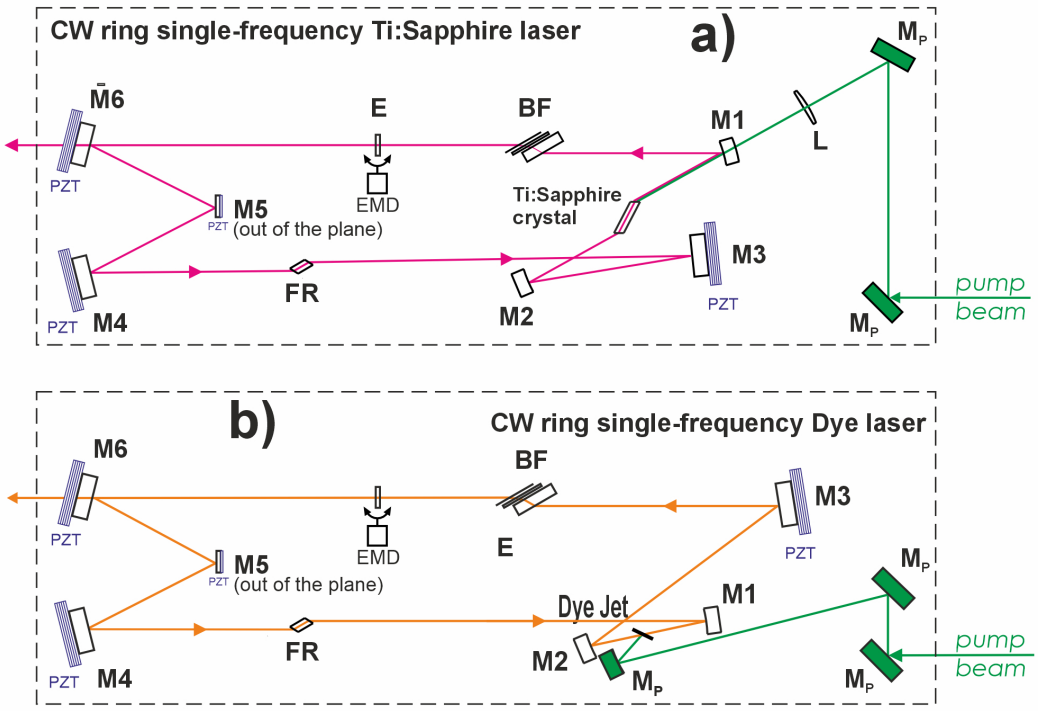

Figure 2. Configurations of the studied continuous wave ring titanium sapphire laser (**a**) and the continuous wave ring dye laser (**b**): M1–M6—cavity mirrors, BF—birefringent filter, FR—Faraday rotator, EMD—electromechanical driver, E—F–P étalon, PZT—piezoelectric transducer, L—lens.

Six mirror configurations for these lasers were proposed in [28]. Their distinction from conventional bow tie laser cavity layouts lies in the way the travelling wave is organised: in bow tie arrangements, the rotation of the polarisation plane of the emitted light introduced by the Faraday element is counteracted by an opposite rotation caused by a phase plate (for example, a crystalline quartz plate set at the Brewster angle) for the wave travelling in one direction of the ring cavity. In six mirror configurations, this compensation is achieved with a single mirror (M5 in Figure 2) that is taken out of the cavity plane. Consequently, the additional phase plate is unnecessary in the latter case. The Faraday rotator does not need to impose significant losses on the waves travelling in opposite directions; a modest difference of less than 1% is sufficient [29]. Both bow tie and six mirror configurations are found in commercial lasers: bow tie in Coherent MBR 110 Ti:Sapphire laser, M Squared SolsTiS; six mirror in Spectra Physics Matisse ring lasers, Tekhnoscan TIS(DYE)-SF-07(7). Bow tie schemes are more common, although six mirror schemes are also successfully used in various applications—from spectroscopy [30–34] to quantum technologies [35–39].

A three-component, birefringent filter made of crystalline quartz was employed as the coarse selector [40,41]. The first plate had a thickness of 0.35 mm, the plate thickness ratio was 1:4:13, and the optical axis was parallel to the plane of the plates. The choice of a filter configuration with the optical axis in the plate plane is driven by the ease of assembly (there is no need to guess the correct orientation of one plate relative to the others), and the 1:4:13 thickness ratio was selected to minimise secondary transmission peaks and to keep the third plate thin, as a thick third plate would render the output beam elliptical due to the "walk off" of ordinary and extraordinary waves in the plate.

Etalon: surface reflectivity coefficient R = 0.04 (4% reflection at normal incidence), free spectral range FSR ≈ 0.6, insertion losses—inserting the etalon into the resonator reduces the laser's output power by roughly 10%, tilt angle range 0.1–3.5 °.

It should be noted that the usable spectral range of the birefringent filter is determined by the spectral bandwidth of the cavity mirrors (~100 nm), not by the gain bandwidth of the active medium (Ti:Sapphire/Dye lasers), which is considerably broader. The usable spectral bandwidth of the cavity mirrors is limited by the low-loss requirement (0.1% or less). While the mirrors' spectral bandwidth can be broadened, this would result in substantially higher radiation losses.

With this selector (other selecting elements being absent), the line width of the ring Ti:Sa laser (Figure 2a) varied with the laser output power (up to 2 W) and reached as much as 30 GHz. Consequently, one of the requirements for the fine selector was that the spacing between adjacent transmission peaks of the birefringent filter exceed 30 GHz, ensuring that only a single fine selector transmission peak lies within the main transmission peak of the birefringent filter.

The algorithm for etalon parameter selection is as follows:

(1) Choose the étalon FSR (and thus its thickness) so that it exceeds both the line width set by the coarse selector (30 GHz for Ti:Sapphire, 35 GHz for dye lasers) and the planned continuous tuning range. A modest excess of 15–20% is advisable; a very large excess would make the étalon impractically thin.
(2) Decide whether to increase the reflectivity of the uncoated etalon faces (which is ≈0.04% for fused silica) by applying additional coatings. In the ideal case no extra coatings are required to obtain a stable single-frequency regime.

Extra coatings are disadvantageous because they typically raise the nonselective losses introduced by the étalon. A major source of these losses is the mismatch between the reflectivity coefficients of the two faces. Achieving perfectly identical coatings on both sides of a solid etalon is difficult in practice, so the actual coating characteristics differ, leading to increased nonselective loss.

In principle, at relatively low output powers, a single-frequency regime can be achieved even without an étalon (using only a birefringent filter) [42]. In a ring Ti:Sapphire (or Dye) laser, a single-frequency regime at comparatively high output powers can be obtained with solid-state étalons whose thickness does not exceed 1 mm [43,44]. One important consideration is that single-frequency operation in a Ti:Sapphire laser does not require any additional coatings on the étalon facets for increased surface reflectivity—the natural reflectance of fused silica (about 4%) is sufficient. In a Dye laser, which exhibits a higher gain in the active medium, the intrinsic reflectance of a thin-étalon surface is inadequate to sustain single-frequency generation; consequently, the surface reflectivity of the étalon is raised to roughly 20–30%. A comparable narrowing of the étalon's transmission peak can be achieved not by increasing the surface reflectivity but by enlarging its base thickness by a factor of 2.5–3. In this case the étalon can remain uncoated and be used as a fine selector both in a ring Ti:Sapphire laser and in a ring Dye laser, i.e., across a broad spectral range. In line with these considerations, a 2.5 mm thick uncoated fused-silica étalon was tested as a fine selector in a ring Ti:Sapphire laser and in a ring Dye laser. It was found that such an étalon provides single-frequency operation in these lasers at output powers up to 1 W for the Dye laser and 2 W for the Ti:Sapphire laser. The laser parameters: cavity length—650 mm, pump power—10 W at 532 nm (Coherent Verdi V 10), Ti:Sapphire crystal with a 0.15% Ti_2O_3 concentration (figure of merit ≈ 250).

Spectra of the tuneable continuous-wave ring Ti:Sapphire laser and the Dye laser equipped with the proposed set of selectors are shown in Figure 3.

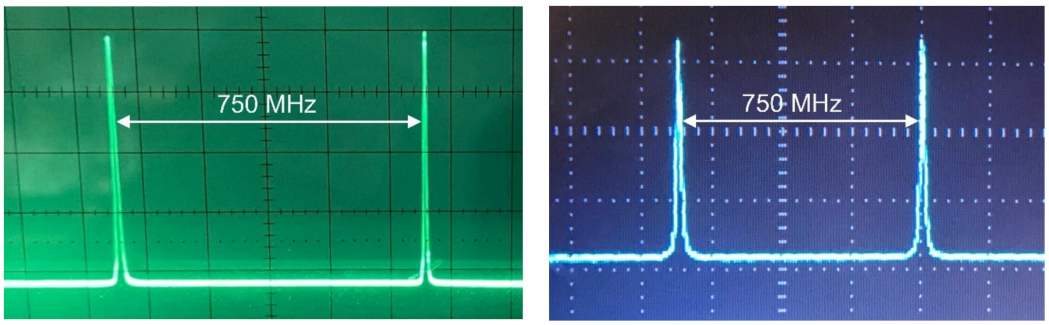

Figure 3. Emission spectra of the CW ring Ti:Sapphire laser (**left**) and the Dye laser (**right**) with the proposed set of selectors, recorded with a scanning confocal F–P interferometer (FSR = 750 MHz, finesse ≈ 30–50 [45]). Y axis: intensity (a.u.), X axis: scanning time. The laser schematics are shown in Figure 2.

The main advantage of the identified set of selectors is their ability to operate over a broad spectral range. Powerful single-frequency generation at a chosen wavelength can be achieved by various means (for example, using injection locked continuous wave Ti:Sapphire or Dye ring lasers [46,47]), but the proposed selector suite enables the realisation of full spectral potential of CW Ti:Sapphire and Dye ring lasers.

4. Continuous Tuning of the Generation Frequency

Continuous tuning of the output frequency is achieved by gradual adjustment of the laser cavity length. In practice, one or more cavity mirrors are mounted on piezoelectric actuators (PZT). The sensitivity of certain multilayer PZT is a few micrometres per kilovolt, which permits the laser's generation frequency to be varied by 1–5 GHz when the drive voltage applied to the PZT is swept between –250 V and +250 V. However, if the fine selector remains stationary, the actual change in the laser's generation frequency does not exceed ±½ of the resonator's free spectral range. Exceeding this limit causes the laser to hop to the next longitudinal mode of the cavity, and so on. Consequently, the generation frequency will vary only around the same spectral region defined by the transmission peak of the fine selector.

To overcome this limitation, the transmission peak of the fine selector must be re-tuned synchronously (or quasi synchronously) with the longitudinal cavity mode of the laser. Proportional control of the PZT-driven cavity mirrors and the electromechanical driver of the fine selector can increase the effective frequency shift, but the improvement is modest because of the differing non-linearities in the transfer functions of the PZT and the electromechanical driver. For the broadest attainable smooth frequency tuning range, an active "locking" of the fine selector transmission peak to the cavity mode is required.

The following method may be used to implement this locking. The transmission peak position of the fine selector is modulated at some low frequency (for example, 1 kHz) within a narrow spectral region close to the cavity mode. It should be noted that not every electromechanical driver is capable of operating at such a high frequency. In some cases, to achieve rapid modulation, the galvanometer (electromechanical driver) is fitted with an additional small piezo electric transducer (PZT) that can modulate the tilt of the étalon at high speed [48], or the etalon is made from an electro-optical crystal ($LiNbO_3$, for example) and modulation is carried out by applying a voltage directly to the crystal [49].

The modulation amplitude of the étalon on the one hand must be kept relatively small so as not to induce periodic jumps of the laser's oscillation frequency onto neighbouring cavity modes (which would occur if the étalon "wiggles" excessively). On the other hand, the modulation amplitude must be sufficiently large to produce a detectable modulation of the laser's output (to get well-defined error signal). With an appropriate choice of

étalon modulation amplitude, the resulting modulation of the laser's output power does not exceed 1%. The variation in output power amplitude when the transmission peak of the fine selector is misaligned with a cavity mode is illustrated in Figure 4. This change in modulation amplitude can be used as an error signal to actively lock the fine selector transmission peak to the cavity mode. Active locking thus enables the full range of continuous generation frequency adjustment provided by one or more PZTs, on which the cavity mirrors are mounted.

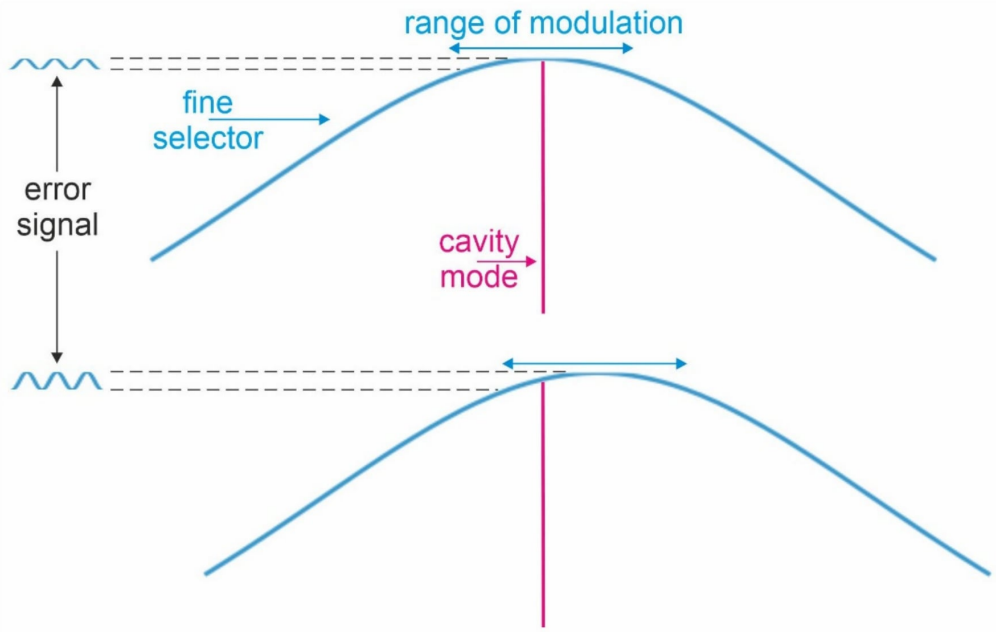

Figure 4. Error signal amplitude variation when the fine selector transmission peak and the longitudinal cavity mode become misaligned.

The experimentally identified pair of selectors that secure single-frequency operation in continuously tuneable Ti:Sapphire and Dye lasers made it possible to achieve continuous frequency scanning over about 4.8 GHz for the Ti:Sapphire laser and 5.4 GHz for the Dye laser under the following conditions. The three cavity mirrors (M3, M4, M6—see Figure 2) were displaced by three multilayer piezo actuators (sensitivity 4 μm/kV) driven with a ± 250 V control voltage. The étalon E was mounted on the axis of a super compact, high-speed electromechanical driver (Cambridge Technologies 6200H galvanometer driver), which can both rotate the étalon smoothly and modulate its tilt angle at 1 kHz for active locking to the cavity mode. An error signal was detected synchronously, integrated, amplified, and fed back into the opposite phase to the electromechanical drive to close the feedback loop.

Active locking of the étalon's transmission peak to the cavity mode, which compensates the nonlinearity of the piezo electric transducer (PZT) and the electromechanical drive, still requires a further correction for the intrinsic nonlinearity of the étalon itself. The tilt angle of the étalon is proportional to the square of the change in the transmission peak frequency. Consequently, to obtain a linear relationship between the change in transmission peak frequency and the control voltage/current supplied to the electromechanical drive, the drive must be fed with a signal that is the square root of the control voltage/current. This linearisation can be performed at the analogue level (for example, using an AD538 precision square root chip). Linearising the dependence of the transmission peak frequency shift on étalon tilt, together with the active locking of the étalon to the resonator mode, allowed the use of a solid étalon whose tilt is controlled by a super compact, high-speed galvanometer motor, thereby providing continuous frequency tuning of the tuneable laser over an extended range.

It is worth noting that modern compact high-speed galvo scanners (Cambridge Technologies 6200 H, Sino Galvo 1105, ScannerMAX Compact 506, and similar devices) make it feasible to employ solid étalons for controlling the generation frequency of a tuneable laser across several gigahertz. Previously this required a fine selector based on a F–P interferometer with an air gap [12], which considerably complicated alignment and operation. The availability of compact, high-speed galvo scanners virtually eliminates the need for air gap F–P interferometers as fine selectors in tuneable lasers.

A solid étalon with a relatively short base (a few millimetres) is also advantageous because the region over which continuous frequency scanning can be performed is relatively large. In practice, it is limited only by the spacing between adjacent transmission peaks of the fine selector, i.e., the étalon. With a base of, let us say, 2.5 mm, this spacing corresponds (taking quartz's refractive index into account) to roughly 41 GHz. Achieving such a substantial, continuous adjustment in the laser cavity length with piezo actuators is not always possible; for larger cavity length variations a small, smooth tilt of a quartz plate near the Brewster angle is sometimes employed [13]. The achievable shift can also be increased by using a thicker plate.

Thus, a solid étalon with a relatively short base (a few millimetres) functions as an efficient fine selector, not only isolating a single generation frequency in a continuously tuneable, widely reconfigurable ring laser, but also permitting smooth tuning of that frequency over a comparatively wide range (Figure 5).

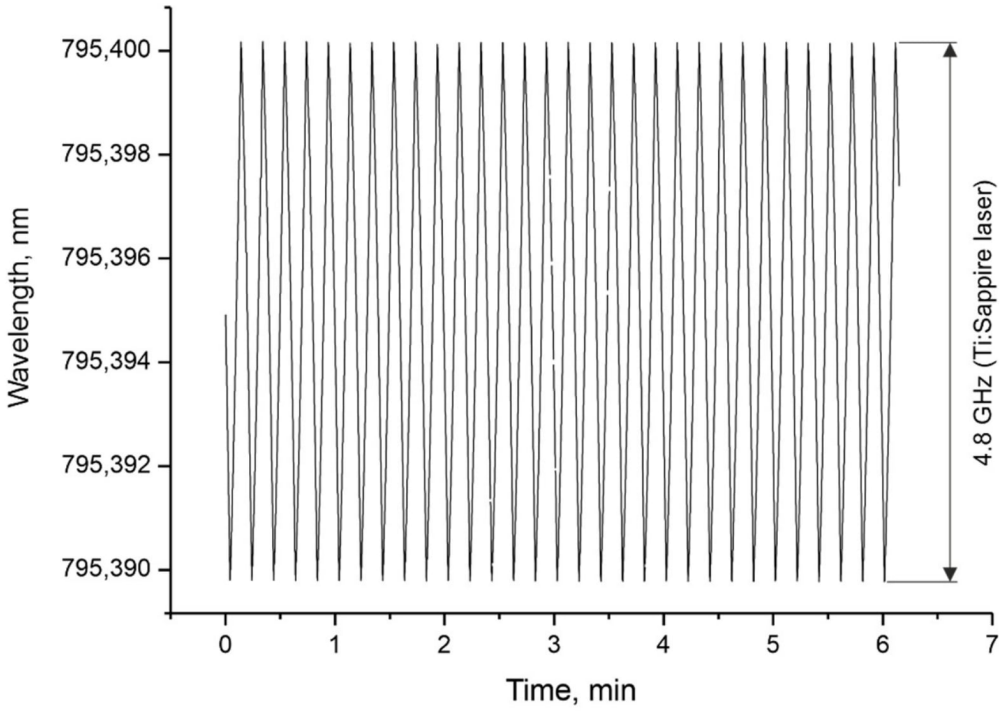

Figure 5. Smooth frequency tuning in a Ti:Sapphire laser.

The synchronisation of the resonator's piezo-ceramic actuators with the reference étalon during a smooth frequency scan (Figure 5) is reliable and remains intact in the absence of external acoustic or mechanical perturbations. This synchronisation technique does not affect the intrinsic frequency drift, which is primarily dictated by the laser-structure materials (thermal expansion and contraction) and amounts to roughly 50 MHz/min. During the smooth scan, the piezo-ceramic of mirror M5 is not used; that actuator can be reserved for active frequency stabilisation, if required. In the unstabilised regime, the Ti:Sapphire laser exhibits a linewidth of 3–5 MHz, while the dye laser shows 8–10 MHz.

With active stabilisation using the reference interferometer, the linewidths can be reduced dramatically: about 10 kHz for the Ti:Sapphire laser and around 100 kHz for the Dye laser.

Another way to achieve smooth frequency scanning of continuous wave Ti:Sapphire (or Dye) ring lasers over a relatively broad spectral range is to introduce an additional intra-cavity nonlinear loss [50,51]. However, this approach cannot be regarded as optimal because the extra intra-cavity loss reduces the laser's conversion efficiency at the operating wavelength.

Another modulation-free method for ensuring synchronous scanning of the fine selector's transmission peak and the cavity mode is the use of a thin étalon made of a birefringent material. In this case, the polarisation state of the radiation reflected from the reference is monitored [52,53]. When the fine selector's transmission peak and the cavity mode are desynchronized, this state changes.

It should be noted that in publications [50–53] by Prof. H. Lu and co-authors, similar approaches are employed to achieve single-frequency operation with Ti:Sapphire lasers, but without modulation of the étalon's tilt angle. Their étalons are fabricated from birefringent or electro-optic crystals and are sometimes combined with nonlinear losses. The solution proposed in the present manuscript uses a very simple étalon made of fused quartz. Modulating its tilt angle only induces a slight modulation of the laser's output power and does not cause any appreciable modulation of the laser frequency.

5. Conclusions

An optimal combination of wavelength selectors for widely tuneable lasers has been identified, enabling single-frequency generation and frequency tuning over a few GHz, with the potential to extend this range to several tens of GHz. Employing a modern compact high-speed galvo scanner to tilt a solid étalon allows automatic locking of its transmission peak to the cavity mode and continuous frequency tuning across an expanded range. F–P interferometers with an air gap, previously used as fine selectors for single-frequency tuneable ring lasers, have become obsolete and are unlikely to be employed in future designs. The optimised set of selectors for single-frequency tuneable lasers offers relative ease of alignment and operation.

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Data Availability Statement: Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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